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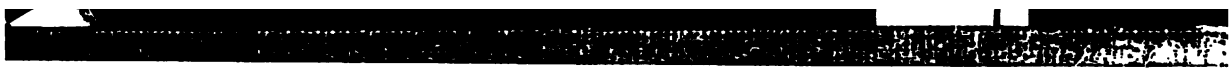

DEPARTMENT OF THE INTERIOR

FRANKLIN K. LANE, Secretary

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, Director

Professional Paper 102

THE INORGANIC CONSTITUENT MARINE INVERTEBRATES

BY

FRANK WIGGLESWORTH CLARKE

AND

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THE INORGANIC CONSTITUENTS OF MARINE INVERTEBRATES.

By FRANK WIGGLESWORTH CLARKE and WALTER CALHOUN WHEELER.

INTRODUCTION.

That many important rocks were once marine sediments and that animals and plants shared in their formation is one of the commonplaces of geology. Coralline limestones, shell limestones, and crinoidal limestones are among the most familiar illustrations of this statement. That corals and shells furnish calcium carbonate to the sediments, that radiolarians and diatoms are siliceous, and that vertebrate animals, some crustaceans, and a few brachiopods are more or less phosphatic are also well-known facts, which, however, have been determined in a more or less desultory way. No systematic investigation to ascertain just what substances each class of organisms contributes to the sediments seems to have been made, and the present research is an attempt to cover the ground a little more thoroughly than it has been covered heretofore. Completeness is, of course, impossible, but something of a foundation for future work we have tried to lay.

Although many analyses of corals and molluscan shells are on record, some important groups of organisms have received only slight attention, and little has been done heretofore toward determining the composition of their tests or skeletons. The few published data, moreover, have been generally but not always incomplete in certain important particulars, especially with regard to the localities from which the specimens analyzed were obtained, the depth of water in which each creature lived, and the temperature of its habitat. Even in our own work some of these details are lacking, but their great significance when known is strikingly evident in the study of such groups of animals as the echinoderms and alcyonarians. Furthermore, some of the older analyses are unsatisfactory for other reasons, for many of them were made to determine single facts, such, for instance, as the proportion of magnesium carbonate alone; and in others such important constituents as organic matter were not taken into account, an omission that is especially serious, for it renders the accurate comparison of the analyses with others impossible. In the shells of mollusks the proportion of organic matter is small, but in the echinoderms, alcyonarians, and phosphatic brachiopods it is relatively large, ranging from 10 to even 40 per cent or more. This statement, however, must not be misconstrued; it refers, of course, only to the specimens, dried or alcoholic, which are actually analyzed. In order to compare the analyses, therefore, so as to determine the true composition of the inorganic shells or skeletons, the very variable amounts of organic matter must be rejected, and the remainders recalculated to 100 per cent. Relations then appear which are not recognizable when the crude unreduced analyses are compared. Any one of our tables of analyses will show this fact very clearly.

In a strict sense completeness can not be claimed even for our analyses. Minor constituents which have been detected in shells, corals, and seaweeds, such as lead, copper, and manganese, have been ignored. They occur only in traces and have little or no significance with respect to the larger problem before us. What organisms tend to form limestones and what ones are notably magnesian, phosphatic, or siliceous are the questions which we are attempting to answer. In most of the analyses lime, magnesia, phosphoric oxide, sulphur trioxide, silica, and loss on ignition were determined. Alumina and oxide of iron were also considered and weighed together. The loss on ignition covered carbon dioxide, organic matter, and water. The carbon dioxide was calculated to satisfy the bases, and the amount thus determined, subtracted from the total loss on

ignition, gave a fair but rough estimate of organic matter plus water. From the crude analyses thus obtained the reduced or rational analyses, recalculated to 100 per cent, were computed. These rational analyses are comparable, and give, closely enough, the essential composition of the material which goes to build up the limestones. More refined work would add little toward the solution of our main problem and would require much tedious labor. In the following pages the detailed analyses are given, group by group, together with some of the older published data. After the evidence has been presented a general discussion of its significance will be in order. The analyses, except a few that are specified, were made by Mr. Wheeler.

FORAMINIFERA.

The Foraminifera, because of their enormous abundance, are of great importance in the formation of marine sediments. The globigerina ooze, for example, covers 49,520,000 square miles of the ocean floor, at a depth of 1,996 fathoms, or 3,653 meters. The analyses of it published in the report of the *Challenger* expedition on deep-sea deposits show that it consists mainly of calcium carbonate, with very little magnesia. Foraminifera are also abundant on "coral reefs," and great masses of limestone are composed largely of their remains.

These organisms, however, are so small, rarely larger than the head of a pin, that it is not easy to obtain enough material of any one species for chemical analysis. The difficulty, fortunately, is not insuperable, and with the help of others we have been so fortunate as to obtain representative samples of seven species, as follows:

1. *Pulvinulina menardii* D'Orbigny. *Albatross* station 2573; latitude, 40° 34′ 18″ N.; longitude, 66° 09′ W.; in line from Long Island Sound to Cape Sable; depth of water, 3,188 meters; bottom temperature, 3° C.
2. *Sphærodina dehiscens* Parker and Jones. East Coast of Mindanao, Philippine Islands; latitude, 8° 51′ 45″ N., longitude, 126° 26′ 52″ E.; depth of water, 804 meters.
3. *Tinoporus baculatus* Carpenter. Murray Islands, Torres Strait, Australia.
4. *Orbitolites marginalis* Lamarck. South of Tortugas, Fla., at depth of 29.3 meters.
5. *Orbiculina adunca* Fichtel and Moll. Key West, Fla.
6. *Polytrema mineaccum* Linné. Bahamas.
7. *Quinqueloculina auberiana* D'Orbigny. Same locality as No. 4; analysis by A. A. Chambers.

Analyses of Foraminifera.

	1	2	3	4	5	6	7
SiO_2	14.70	8.55	0.03	0.03	0.11	0.02	0.54
$(Al,Fe)_2O_3$	3.81	4.76	.18	.13	.09		
MgO	1.68	.82	5.03	4.93	4.64	5.09	4.32
CaO	41.36	45.48	47.35	48.92	48.79	47.35	49.02
P_2O_5	(?)	(?)	.00	Trace.	Trace.	(?)	
Ignition	38.12	39.01	46.57	45.20	45.56	46.24	45.54
	99.67	98.62	99.16	99.48	99.19	98.70	99.42
CO_2 needed	34.41	36.63	42.74	43.90	43.43	42.80	43.27
Organic matter, etc	3.71	2.38	3.73	1.30	2.13	3.44	2.27

Rejecting organic matter and water and recalculating to 100 per cent, the analyses assume the following rational form:

Reduced analyses.

	1	2	3	4	5	6	7
SiO_2	15.33	8.89	0.03	0.31	0.11	0.02	0.56
$(Al,Fe)_2O_3$	3.98	4.94	.19	.13	.09		
$MgCO_3$	3.67	1.79	11.08	10.55	10.04	11.22	9.33
$CaCO_3$	77.02	84.38	88.70	89.01	89.76	88.76	90.11
$Ca_3P_2O_8$	(?)	(?)	.00	Trace.	Trace.	(?)	(?)
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

In Nos. 1 and 2 the high percentages of silica and sesquioxides are evidently due to impurities. If they are rejected, the percentages of magnesium carbonate become 5.19 and 2.09, respectively. These two Foraminifera are from deep and presumably cold water. The others are from shallow water in warm regions. A similar difference in the magnesian content of the organisms with regard to temperature appears, with much regularity, in several other series of our analyses, notably in the series of crinoids and alcyonarians.

The only published analyses of Foraminifera that we have been able to find elsewhere appear in H. B. Brady's volume [1] on the material collected by the *Challenger* expedition. Four of these analyses relate to *Orbitolites complanata* var. *laciniata*, collected either at Fiji, or at Tongatabu, Friendly Islands. These analyses are as follows:

1, 2. Two different samples; analyses by C. R. A. Wright and J. T. Dunn.
3. Sample washed with boiling water.
4. Same as No. 3, unwashed; analyses 3 and 4 by J. Gibson.

Analyses of orbitolites.

	1	2	3	4
SiO_2	0.58	0.3	0.14	0.11
Al_2O_3 [a]		2.7		
$(Al,Fe)_2O_3$	.68			
$MgCO_3$	12.52	8.8	9.55	10.50
$CaCO_3$	86.46	88.2	88.74	87.91
	100.24	100.0	98.43	98.52

[a] Including "phosphates of lime and magnesia."

Other analyses, presented by Wright and Dunn, are of *Amphistegina lessonii*, from Cape Verde Islands, and *Operculina complanata*, from near Amboyna, in the Malay Archipelago. The analyses are obscurely stated but give from 4.8 to 4.9 per cent of magnesium carbonate. In a Tertiary fossil, *Nubecularia novorossica*, 26 per cent of magnesium carbonate was found, an amount which probably represents a concentration by leaching. There are also analyses of several siliceous Foraminifera containing from 76.1 to 94.7 per cent of silica. Their tests appear to have been built up of sand grains and are of little or no significance in relation to the main problem of the present investigation. Their remains are not true additions to the sediments.

SPONGES.

The sponges are a rather unsatisfactory group of organisms for chemical analysis, on account of their very porous structure. They are liable to contain inclosed impurities, such as sand or mud, which are difficult to remove entirely. Some sponges are siliceous, some calcareous, and others composed almost wholly of organic matter, the proteid spongin. The ideal method of procedure for our purposes would obviously be to separate the clean siliceous or calcareous spicules and to analyze them alone, but to do that a large amount of material would have to be gone over, and more time would be consumed than we could give to this part of our investigation. As the sponges are of minor importance in relation to the marine sediments, we have followed our usual course, and so have obtained results which are of some significance, even if they are not all that might be desired. Twenty sponges have been examined, more or less completely, as follows:

1. *Euplectella speciosa* Quoy and Gaimard ("Venus's flower basket"). Philippine Islands.
2. *Bathydorus uncifer* F. E. Schulze. Galapagos Islands, *Albatross* station 2818; latitude, 0° 29′ S.; longitude, 89° 54′ 30″ W.; depth of water, 617.4 meters; bottom temperature, 9.9° C.
3. *Halichondria panicea* Johnston. Alaska.
4. *Suberites suberea* Johnston. Unga Island and Popoff Strait. Alaska.
5. *Tethya gravata* Hyatt. Buzzards Bay, Mass.
6. *Pheronema grayi* Kent. Off southwest coast of Ireland, at depth of 1,098 meters.

[1] *Challenger* Report, vol. 9, pp. XVII–XXI, 1884.

7. *Geodia mesotriæna* var. *pachana* Lendenfeld. Off southern California, *Albatross* station 2909; latitude, 32° 22′ N.; longitude, 120° 08′ 30″ W.; depth, 377 meters; bottom temperature, 7.3° C.

8. *Phakellia grandis* Verrill. East part of Browns Bank, nearly east of Cape Cod, between latitudes 40° 30′ and 42° 08′ N. and longitudes 66° to 69° W.; depth, 549 meters.

9. *Chondrocladia alaskensis* Lambe. On beach at Unalaska, Alaska.

10. *Gelliodes grandis* Verrill. Gulf of Maine.

11. *Esperiopsis quatsinoensis* Lambe. Auttu Island, Alaska.

12. *Chalina arbuscula* Verrill. Outer Island, Conn.

13. *Spinosella sororia* var. *crispa* Duchassaing and Michelotti. Harrington Sound, Bermuda.

14. *Euspongia officinalis tubulifera* var. *turrita* Hyatt. Harrington Sound, Bermuda.

15. *Hircinia campana* var. *turrita* Hyatt. Bermuda.

16. *Euspongia officinalis* var. *rotunda* Hyatt. Nassau, Bahama Islands.

17. *Hippospongia equina* var. *meandriformis* Duchassaing and Michelotti. Nassau, Bahamas.

18. *Hippospongia agaricina* var. *dura* Hyatt. Off Duck Key, Florida, at depth of 4.6 meters.

19. *Hippospongia caniculata* var. *gossypina* Duchassaing and Michelotti. Off Rock Island, Florida, at depth of 7.3 meters.

20. *Aplysina hirsuta* Hyatt. Off St. Thomas, Danish West Indies; depth of water, 37 to 42 meters.

The analyses, made by our usual methods, are as follows:

Analyses of sponges.

	1	2	3	4	5	6	7	8
SiO_2	88.56	76.33	74.52	72.92	68.46	65.19	64.96	60.70
$(Al,Fe)_2O_3$	.32	1.05	6.19	1.22	3.71	3.05	.21	2.30
MgO	.00	.48	1.43	.55	.61	Trace.	.38	.23
CaO	.22	2.78	2.33	.33	.89	3.26	.29	.51
P_2O_5	.00	.00	.17	.49	.48	Trace.	Trace.	.46
SO_3	.00	Trace.	.08	.39	.40	.02	.21	(?)
Ignition	10.26	18.60	12.11	22.21	23.02	27.05	31.73	35.84
	99.36	99.24	96.83	98.11	97.57	98.57	97.78	100.04

	9	10	11	12	13	14	15
SiO_2	53.96	52.24	51.94	31.93	3.08	1.31	0.57
$(Al,Fe)_2O_3$	1.64	3.86	1.38	1.44	.77	.96	2.29
MgO	.58	.86	.75	.97	.26	.43	1.60
CaO	1.28	.77	1.77	.97	2.80	7.58	20.01
P_2O_5	.31	.61	.46	.50	.69	.77	.68
SO_3	(?)	.81	(?)	.82	(?)	(?)	(?)
Ignition	41.97	34.64	42.29	61.25	91.32	89.75	75.68
	99.74	93.79	98.59	97.88	98.92	100.80	100.83

Sponges Nos. 16–20 were composed mainly of organic matter, and only loss on ignition was determined. The figures showing this loss are as follows:

	Per cent.
16. *Euspongia officinalis*	96.94
17. *Hippospongia equina*	96.98
18. *Hippospongia agaricina*	95.55
19. *Hippospongia caniculata*	91.72
20. *Aplysina hirsuta*	93.34

In these sponges the inorganic matter is so small that it may only represent impurities, an analysis of which would be meaningless. *Euspongia* and *Hippospongia* are the ordinary bath sponges of commerce.

In several of the analyses, notably in Nos. 3, 5, 7, 10, and 12, the summation is very low, on account of the presence of soluble salts (sea salt), which were not determined. Analyses 1 to 12 represent siliceous sponges, and in Nos. 2 and 6 the siliceous spicules are very conspicuous. No. 1, *Euplectella*, the beautiful "Venus's flower basket," may be taken as the type of these sponges, and its analysis shows that its skeleton is nearly pure opaline silica. Several analyses of siliceous sponge spicules by other chemists lead to similar conclusions. In spicules from

unnamed species J. Thoulet[1] found from 12.88 to 13.18 per cent of water, F. E. Schulze[2] cites an analysis by Maly of spicules from *Poliopogon amadou* which contained 7.16 per cent, and in seven species of siliceous sponges W. J. Sollas[3] found water varying from 6.1 to 7.34 per cent. In all these sponges the spicules or skeletons are composed of amorphous opaline silica. The other constituents shown in our analyses, except organic matter, which is included in the loss on ignition, are probably but not certainly impurities. To this statement one exception may be made. The phosphoric oxide is perhaps a part of the organisms, which contain it not as such but as phosphorus in some organic compound. This, however, is by no means certain. That all the sponges analyzed contain phosphorus in some form, although in small amounts, is clear.

Analysis No. 13, of *Spinosella*, is very high in organic matter, and its precise character is doubtful, at least so far as the chemical evidence goes. Nos. 14 and 15, however, of *Euspongia* and *Hircinia* represent calcareous sponges. Reducing the analyses to standard form, rejecting organic matter, and recalculating to 100 per cent, we have the following figures for their inorganic portions:

Reduced analyses of calcareous sponges.

SiO_2	7.81	1.36
$(Al,Fe)_2O_3$	5.72	5.45
$MgCO_3$	5.37	8.00
$CaCO_3$	71.14	81.64
$Ca_3P_2O_8$	9.96	3.55
$CaSO_4$	(?)	(?)
	100.00	100.00

We can not assign much weight to these reductions, because of the apparent impurities in the specimens analyzed. The presence of magnesia, however, in these sponges is somewhat confirmed by an analysis by O. Bütschli[4] of spicules from a Mediterranean sponge, *Leucandra aspera*. His figures are as follows:

$CaCO_3$	86.76
$MgCO_3$	6.84
Fe_2O_3	.26
$CaSO_4.2H_2O$	1.97
H_2O	3.14
Organic matter	.42
	99.39

If we reject water and organic matter and recalculate to 100 per cent the percentage of magnesium carbonate rises to 7.17. It seems probable, then, that the calcareous sponges are distinctly magnesian, although more analyses are needed to establish the fact.[5]

MADREPORARIAN CORALS.

Madreporarian or stony corals have been repeatedly analyzed and with generally concordant results. Twenty-eight of these corals were studied in the course of this investigation, and with the results two old analyses made in the laboratory of the United States Geological Survey may properly be included. The order of arrangement here is regional, for reasons which will appear later, in our study of the alcyonarians. The list of corals analyzed is as follows:

1. *Balanophyllia floridana* Pourtalès. South of Key West, Fla.; depth of water, 165 meters.
2. *Paracyathus defilipii* Duchassaing and Michelotti. South of Key West; depth, 165 meters.
3. *Dendrophyllia cornucopia* Pourtalès. *Fish Hawk* station 7286. Gulf Stream, off Key West; latitude, 24° 18′ 00″ N.; longitude, 81° 47′ 45″ W.; depth, 243 meters; bottom temperature, 11.9° C.

[1] Compt. Rend., vol. 98, p. 1000, 1884.
[2] *Challenger* Report, vol. 21, p. 28, 1887.
[3] *Challenger* Report, vol. 25, p. xlviii, 1888.
[4] K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.
[5] On manganese and iron in sponges, see Cotte, J., Soc. biologie Compt. rend., vol. 55, p. 139, 1903. Traces of manganese were noted in our own analyses.

4. *Siderastrea radians* Pallas. Shoal water, Ragged Keys, Fla.
5. *Porites furcata* Lamarck. Shoal water, Ragged Keys, Fla.
6. *Favia fragum* Esper. Shoal water, Tortugas, Fla.
7. *Eusmilia aspera* Dana. Shoal water, Tortugas, Fla.
8. *Oculina diffusa* Lamarck. Shoal water, Tortugas, Fla.
9. *Cladocora arbuscula* Lesueur. Tortugas, Fla.; depth, 27.5 meters.
10. *Agaricia purpurea* Lesueur. Reef, Loggerhead Key, Tortugas, Fla.
11. *Orbicella annularis* Ellis and Solander. Reef, Loggerhead Key, Fla.
12. *Dasmosmilia lymani* Pourtalès. *Albatross* station 2087; latitude, 40° 06′ 50″ N.; longitude 70° 34′ 15″ W.; depth, 119 meters; bottom temperature, 10° C.
13. *Flabellum alabastrum* Moseley. *Albatross* station 2677; latitude, 32° 39′ N.; longitude, 76° 50′ 30″ W.; between the Bahamas and Cape Fear; depth, 875 meters; bottom temperature, 4.5° C.
14. *Madrepora prolifera* Linné. *Albatross* stations 2662–2672, between the Bahamas and Cape Fear; depth, 512–894 meters; bottom temperature, 6°–7° C.
15. *Dendrophyllia profunda* Pourtalès. Locality, etc., as under No. 14.
16. *Madracis decactis* Lyman. Shoal water, Bermuda.
17. *Deltocyathus italicus* Michelotti. *Albatross* station 2750; latitude, 18° 30′ N.; longitude, 63° 31′ W.; depth, 908 meters; bottom temperature, 7° C.
18. *Acropora cervicornis* Lamarck. Shoal water, South Bight, Bahamas.
19. *Orbicella cavernosa* Linné. Reef, Light House Point, Andros Island, Bahamas.
20. *Mæandra clivosa* Ellis and Solander. Locality as under No. 19.
21. *Mæandra labyrinthiformis* Linné. Reef, Golding Cay, Andros Island, Bahamas.
22. *Mussa* aff. *M. dipsacea* Dana. Reef, Golding Cay.
23. *Porites clavaria* Lamarck. Reef, Golding Cay.
24. *Porites astreoides* Lamarck. Reef, Golding Cay.
25. *Flabellum pavonium* var. *paripavoninum* Alcock. *Albatross* station 4080; north coast of Maui, Hawaiian Islands; depth, 326 to 369 meters; bottom temperature, 13.5° C.
26. *Madracis kauaiensis* Vaughan. *Albatross* station 3982; vicinity of Kauai, Hawaiian Islands; depth, 426–435 meters; bottom temperature, 9.1° C.
27. *Flabellum* sp. *Albatross* station 5273; latitude, 14° 03′ N.; longitude, 120° 27′ 45″ E.; China Sea, near southern Luzon; depth, 102.5 meters.
28. *Desmophyllum ingens* Moseley. *Albatross* station 2785; latitude, 48° 09′ S.; longitude, 74° 36′ W.; off coast of Chile; depth, 822 meters; bottom temperature, 8.3° C.

The actual analyses appear in the following tables. Sulphates were rarely determined, but they are unimportant.

Analyses of corals.

	1	2	3	4	5	6	7
SiO_2	0.09	0.42	0.09	0.12	0.11	0.28	0.00
$(Al,Fe)_2O_3$	.69	.35	.11	.11	.10	.12	.04
MgO	.49	.39	.19	.21	.36	.18	.21
CaO	51.46	52.03	51.71	51.23	51.61	53.69	53.25
SO_3	(?)	.00	(?)	(?)	(?)	(?)	(?)
P_2O_5	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
Ignition	47.32	44.62	46.23	47.21	46.76	44.44	44.90
	100.05	97.81	98.33	98.88	98.94	98.71	98.40
CO_2 needed	39.97	41.31	40.84	41.48	40.95	42.38	42.08
Organic matter, etc	7.35	3.31	5.39	5.73	5.81	2.06	2.82

	8	9	10	11	12	13	14
SiO_2	0.07	0.30	0.04	0.00	0.20	0.09	0.19
$(Al,Fe)_2O_3$	.05	.08	.00	.03	.27	.11	.07
MgO	.19	.05	.28	.27	.29	.17	.06
CaO	53.90	53.31	53.87	53.58	53.79	53.54	53.48
SO_3	(?)	(?)	(?)	(?)	.10	(?)	.12
P_2O_5	Trace.	Trace.	.00	.00	Trace.	Trace.	Trace.
Ignition	44.57	44.83	44.62	44.76	44.47	44.80	44.50
	98.78	98.57	98.81	98.64	99.12	98.71	98.42
CO_2 needed	42.56	41.94	42.64	42.40	42.52	42.26	42.03
Organic matter, etc	2.01	2.89	1.98	2.36	1.95	2.54	2.47

Analyses of corals—Continued.

	15	16	17	18	19
SiO_2	0.33	0.04	0.21	0.00	0.(
$(Al,Fe)_2O_3$	.07	.13	.25	.06	.(
MgO	.05	.34	.25	.20	.3
CaO	53.83	52.78	53.38	52.47	53.(
SO_3	(?)	(?)	(?)	(?)	(?)
P_2O_5	Trace.	Trace.	Trace.	Trace.	.(
Ignition	44.49	45.33	44.49	45.77	45.2
	98.77	98.62	98.58	98.50	98.7
CO_2 needed	42.35	41.84	42.41	41.45	42.(
Organic matter, etc	2.14	3.49	2.28	4.32	3.1

	22	23	24	25	26
SiO_2	0.14	0.04	0.02	0.40	0.(
$(Al,Fe)_2O_3$	.05	.09	.02	.53	.1
MgO	.04	.17	.18	.20	.1
CaO	53.34	52.12	53.84	53.22	53.2
SO_3	(?)	(?)	(?)	(?)	(?)
P_2O_5	Trace.	Trace.	Trace.	Trace.	Trac
Ignition	44.81	45.84	44.98	44.31	44.8
	98.38	98.26	99.04	98.66	98.9
CO_2 needed	41.95	41.14	42.50	42.04	42.8
Organic matter, etc	2.86	3.70	2.48	2.27	1.9

The two other analyses of corals, which were made some years ago in the St do not appear in the foregoing table because they are stated in somewhat differ are, however, included in the following table of reduced analyses, in which the culated to 100 per cent and as definite salts, with organic matter and wate two in question are as follows:

29. *Siderastrea* sp. Bermuda; analysis by L. G. Eakins.
30. Coral, species undetermined. Panama; analysis by W. T. Schaller.

Reduced analyses.

	1	2	3	4
SiO_2	0.10	0.44	0.10	0.1
$(Al,Fe)_2O_3$	.74	.37	.12	.1
$MgCO_3$	1.11	.87	.43	.4
$CaCO_3$	98.05	98.32	99.35	99.2
$CaSO_4$	(?)	.00	(?)	(?)
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trac
	100.00	100.00	100.00	100.(

	7	8	9	10
SiO_2	0.00	0.07	0.31	0.(
$(Al,Fe)_2O_3$	.04	.05	.08	.(
$MgCO_3$	.46	.41	.11	.(
$CaCO_3$	99.50	99.47	99.50	99.3
$CaSO_4$	(?)	(?)	(?)	(?)
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	.(
	100.00	100.00	100.00	100.(

Reduced analyses—Continued.

	13	14	15	16	17	18
SiO_2	0.09	0.20	0.34	0.04	0.22	0.00
$(Al,Fe)_2O_3$	.12	.07	.07	.14	.26	.06
$MgCO_3$	.37	.14	.12	.76	.54	.45
$CaCO_3$	99.42	99.38	99.47	99.06	98.98	99.49
$CaSO_4$	(?)	.21	(?)	(?)	(?)	(?)
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00

	19	20	21	22	23	24
SiO_2	0.10	0.02	0.00	0.15	0.04	0.02
$(Al,Fe)_2O_3$	.00	.04	.04	.05	.10	.02
$MgCO_3$	.77	.73	.57	.09	.37	.40
$CaCO_3$	99.13	99.21	99.39	99.71	99.49	99.56
$CaSO_4$	(?)	(?)	(?)	(?)	(?)	(?)
$Ca_3P_2O_8$	.00	.00	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00

	25	26	27	28	29	30
SiO_2	0.41	0.06	0.07	0.14	0.23	1.25
$(Al,Fe)_2O_3$	.55	.11	.15	.06	Trace.	.59
$MgCO_3$	.43	.33	.37	.59	.42	.59
$CaCO_3$	98.61	99.50	99.41	99.21	99.35	97.57
$CaSO_4$	(?)	(?)	(?)	(?)	(?)	(?)
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	(?)	(?)
	100.00	100.00	100.00	100.00	100.00	100.00

These analyses are remarkably concordant and show that the stony corals contain little besides calcium carbonate. Silica and sesquioxides are probably extraneous; magnesia is altogether subordinate, although fairly regular in its amount; phosphates occur only in traces. The older analyses all tell the same story, except that in six analyses by S. P. Sharples[1] of corals from the Gulf Stream from 0.27 to 0.84 per cent of calcium phosphate was determined. In five analyses of Brazilian corals, L. R. Lenox[2] found from 0.42 to 0.54 per cent of magnesium carbonate, quantities like those appearing in our tables. In short, the uniformity of the data is so marked that it is unnecessary to reproduce all the published analyses here.[3]

ALCYONARIAN CORALS.

The alcyonarians, which include the red corals, the gorgonias, or sea fans, and other similar, generally branching forms, differ from the madrepores in being notably magnesian. To this rule one exception is known, the genus *Heliopora*, which stands quite alone and resembles the ordinary corals not only in structure but also in chemical composition.[4] With this exception, the alcyonaria are chemically similar to the crinoids, but some genera are much richer in phosphates. In some respects the alcyonarians are difficult to deal with analytically, for many of them have a horny axis, composed chiefly of organic matter, surrounded by a cortex or envelope

[1] Am. Jour. Sci., 3d ser., vol. 1, p. 168, 1871.

[2] Mus. Comp. Zool. Bull., vol. 44, p. 264, 1904. In a memoir by J. C. Branner on sandstone reefs.

[3] See also B. Silliman, jr., Am. Jour. Sci., 2d ser., vol. 1, p. 189, 1846, for 31 analyses of corals from the South Pacific and the Indian Ocean; G. Forchhammer, Neues Jahrb., 1852, p. 854, on magnesia in shells and corals; H. W. Nichols, Field Columbian Mus., Pub. 111, p. 31, 1906; also for determinations of magnesia. In *Oxlaria dædalea* from Abyssinia ne found 0.35 per cent of $MgCO_3$. A. G. Högbom, Neues Jahrb., 1894, Band 1, p. 262, in two Bermuda corals found 0.36 and 0.62 per cent of $MgCO_3$.

[4] See H. W. Moseley, Philos. Trans., vol. 166, p. 91, 1876, on the structural relations of *Heliopora*.

which is largely calcareous. These two portions of the structure are so unlike in composition that imperfections in a sample taken for analysis may lead to very uncertain conclusions.

The list of alcyonarians analyzed is as follows:

1. *Heliopora cerulea* Pallas; blue coral. Southern Philippines. The blue color consists of organic matter.[1]
2. *Tubipora purpurea* Lamarck. Singapore, Straits Settlements; latitude, 1° 20′ N.; longitude, 103° 50′ E.
3. *Corallium elatior* Ridley; a red coral. Murotsu, Tosa (Shikoku), Japan; latitude, about 33° N.
4. *Primnoa reseda* Verrill. East of Nova Scotia; depth of water, 366 meters; latitude, 42° 16′ N.; longitude, 63° 15′ W.
5. *Lepidisis caryophyllia* Verrill. Off Nantucket Shoals, *Albatross* station 2037; latitude, 38° 53′ 00″ N.; longitude, 69° 23′ 30″ W.; depth, 3,168 meters; bottom temperature, 3.3° C.
6. *Pennatula aculeata* Dana. St. Peters Bank and Banquereau; *Albatross* station 2470; latitude, 44° 47′ N.; longitude, 56° 33′ 45″ W.; depth, 410 meters; bottom temperature, 4.5° C.
7. *Paramuricea borealis* Verrill. Southwest edge of the Grand Banks; depth, 641 to 732 meters.
8. *Paragorgia arborea* Milne-Edwards and Haime. La Have Ridge, off Nova Scotia.
9. *Alcyonium carneum* L. Agassiz. Southwest of Stellwagen Bank, off Race Point Light, Cape Cod, Mass.; depth, 57 meters; bottom temperature, 3.9° C.
10. *Gorgonia suffruticosa* Dana. Fiji Islands. Cortex and axis together.
11. *Gorgonia acerosa* Pallas. East end of Long Cay, Nassau, Bahamas; latitude, 25° 5′ 6″ N. Cortex and axis.
12. *Gorgonia acerosa*. Cæsars Creek, southern Florida; latitude, 23° 30′ N., approximately. Cortex alone.
13. *Muricea humilis* Milne-Edwards. Parahyba do Norte, Brazil; latitude, 7° to 8° S.
14. *Muricea echinata* Valenciennes. Cape San Lucas, Lower California; latitude, 22° 52′ N.
15. *Plexaurella grandiflora* Verrill. Mar Grande, Bahia, Brazil.
16. *Ctenocella pectinata* Valenciennes. Torres Straits, Australia; latitude, about 10° S.
17. *Xiphogorgia anceps* Pallas. Cæsars Creek, southern Florida; latitude 23° 30′ N., approximately.
18. *Rhipidogorgia flabellum* Linné. Bermuda; latitude, about 32° N.
19. *Rhipidogorgia flabellum*. East side of Andros Island, Bahamas; latitude, about 25° N.
20. *Leptogorgia pulchra* Verrill. La Paz, Gulf of California; latitude, 24° 16′ N.
21. *Leptogorgia rigida* Verrill. Cape San Lucas, Lower California; latitude, 22° 52′ N.
22. *Phyllogorgia quercifolia* Dana. Fernando de Noronha, Brazil; latitude, 3° 50′ S.; longitude, 32° 25′ W.

Analyses of alcyonarians.

	1	2	3	4	5	6	7	8
SiO_2	0.14	1.36	0.00	0.09	0.11	1.21	0.26	0.13
$(Al,Fe)_2O_3$	.07	.55	.14	.64	.05	.72	.18	.02
MgO	.16	5.67	5.44	2.15	3.16	2.62	2.27	3.71
CaO	54.42	46.60	48.65	37.76	49.87	35.67	29.92	43.47
SO_3	.29	.68	.77	.71	.37	.35	1.64	1.10
P_2O_5	Trace.	Trace.	.18	.28	Trace.	1.02	.39	.22
Ignition	44.33	44.75	46.01	57.58	45.70	59.26	77.32	50.48
	99.41	99.61	101.19	99.21	99.26	100.85	100.98	99.13
CO_2 needed	42.78	42.48	42.87	31.38	42.43	29.76	24.74	37.44
Organic matter, etc	1.55	2.27	3.14	26.20	3.27	29.50	41.58	13.04

	9	10	11	12	13	14	15
SiO_2	6.84	0.26	0.13	0.03	0.44	0.09	0.38
$(Al,Fe)_2O_3$	2.20	.13	.13	.13	.06	.05	.13
MgO	1.66	3.03	3.54	3.51	5.25	4.58	5.61
CaO	14.04	22.32	28.73	26.48	42.14	38.04	40.94
SO_3	.31	1.51	.68	1.33	.89	1.35	Trace.
P_2O_5	2.32	.10	.99	.73	.24	.30	Trace.
Ignition	72.24	71.46	62.34	63.49	51.59	54.09	52.49
	99.61	100.81	96.54	95.70	100.61	98.50	99.55
CO_2 needed	10.34	19.94	25.17	23.26	38.13	33.91	38.34
Organic matter, etc	61.70	51.52	37.17	40.23	13.43	20.18	14.15

[1] See Moseley, H. W., op. cit., and Bourne, G. C., Philos. Trans., vol. 186, p. 455, 1895.

The low summation of Nos. 11 and 12 is due to inclosed or adherent sea salts. In No. 12 the amount of water-soluble matter was determined and proved to be 4.71 per cent, of which 0.55 per cent was SO_3. Applying these corrections to the analysis the summation becomes 99.96.

	16	17	18	19	20	21	22
SiO_2	0.17	0.08	0.12	0.16	0.06	0.21	0.26
$(Al,Fe)_2O_3$	.10	.04	.16	.06	.02	.16	.19
MgO	5.90	3.52	3.42	4.22	4.60	5.14	5.59
CaO	37.05	27.19	27.41	32.23	33.59	36.15	34.62
SO_3	.79	1.28	.80	1.17	1.21	.93	.93
P_2O_5	.32	.51	.28	.86	2.67	2.78	2.97
Ignition	56.15	65.56	65.67	62.10	55.89	55.39	55.28
	100.48	98.18	97.86	100.80	98.04	100.76	99.84
CO_2 needed	34.87	24.07	25.60	28.51	28.31	30.96	34.14
Organic matter, etc	21.28	41.49	40.07	33.59	27.58	24.43	21.14

The reduced or rational analyses are as follows:

Reduced analyses.

	1	2	3	4	5	6	7	8
SiO_2	0.15	1.40	0.00	0.13	0.11	1.70	0.44	0.15
$(Al,Fe)_2O_3$	.07	.57	.15	.88	.05	1.01	.30	.03
$MgCO_3$	.35	12.23	11.56	6.18	6.92	7.71	8.03	9.05
$CaCO_3$	98.93	84.61	86.57	90.39	92.24	85.62	85.11	88.04
$CaSO_4$	.50	1.19	1.32	1.59	.68	.84	4.69	2.17
$Ca_3P_2O_8$	Trace.	Trace.	.40	.83	Trace.	3.12	1.43	.56
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	9	10	11	12	13	14	15
SiO_2	18.05	0.55	0.22	0.04	0.50	0.11	0.45
$(Al,Fe)_2O_3$	5.80	.28	.22	.24	.07	.06	.15
$MgCO_3$	9.21	13.43	12.52	13.29	12.64	12.28	13.79
$CaCO_3$	52.23	79.84	81.45	79.48	84.47	83.79	85.61
$CaSO_4$	1.36	5.43	1.95	4.08	1.73	2.93	Trace.
$Ca_3P_2O_8$	13.35	.47	3.64	2.87	.54	.83	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	16	17	18	19	20	21	22
SiO_2	0.21	0.14	0.21	0.24	0.09	0.28	0.34
$(Al,Fe)_2O_3$	.13	.07	.28	.07	.03	.21	.26
$MgCO_3$	15.65	13.04	12.64	13.19	13.71	14.13	15.73
$CaCO_3$	81.44	80.96	83.38	80.75	74.99	75.36	72.99
$CaSO_4$	1.69	3.83	2.40	2.95	2.91	2.07	2.11
$Ca_3P_2O_8$	.88	1.96	1.09	2.80	8.27	7.95	8.57
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Analysis No. 1, that of *Heliopora*, might be an analysis of an ordinary coral, being nearly nonmagnesian and hence different from all the others. The material of No. 9, *Alcyonium carneum*, was obviously very impure, containing much admixture of sand or mud. That the species is remarkably rich in calcium phosphate, however, seems to be clear. It needs further investigation upon better material.

In two of the *Gorgonias* the black wiry axis was separately analyzed, although the amount of material was very small. The axis of a *Rhipidogorgia* sp. from Bermuda was also studied and to better advantage. The three analyses are as follows:

	Gorgonia acerosa.	Gorgonia suffruticosa.	Rhipidogorgia?.
SiO_2	0.04	0.39	0.07
$(Al,Fe)_2O_3$	.10	.06	Trace.
MgO	.71	.80	1.03
CaO	.53	1.10	.50
P_2O_5	.31	Trace.	.15
SO_3	.94	1.65	1.90
Ignition	96.45	94.39	95.83
	99.08	98.39	99.48

The axes, evidently, are composed largely of organic matter, and the inorganic portions differ in composition from the more abundant calcareous envelopes. In two of them magnesia is in excess of lime, and in all three the sulphates are conspicuous. To determine the exact chemical nature of these axes would require much material and a longer investigation than we are justified in attempting.

A specimen of *Leptogorgia flammea* Verrill, from the Cape of Good Hope, was also examined, but it was not sufficiently perfect. Much of the cortex had been broken away, leaving an excess of the axis. The partial results obtained, however, showed an exceedingly high proportion of phosphates, and a complete study of the species is much to be desired. Indeed, the genus *Leptogorgia* well deserves an exhaustive investigation, but perhaps more on biological than on geological grounds. The fact that it contributes both magnesium carbonate and calcium phosphate to the marine sediments seems to be established.

Several other analyses of alcyonarians, partial or complete, are on record, and three of them deserve reproduction here. The data are as follows:

1. *Pleurocorallium johnsoni* Gray. From latitude 25° 45′ N., longitude 20° 12′ W., about 160 miles southwest of the Canary Islands; depth of water, 2,791 meters. At that depth the temperature must have been very low, probably not much above 0° C. Analysis by Anderson in *Challenger* Report, Deep-sea Deposits, p. 465, 1891.
2. *Alcyonium palmatum*. Probably Mediterranean.
3. *Corallium rubrum;* the precious red coral. Mediterranean.

Analyses 2 and 3 by O. Bütschli in K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.

Older analyses of alcyonarians.

	1	2	3
$CaCO_3$	93.39	86.25	86.78
$MgCO_3$	6.00	9.38	8.97
"Phosphate"	.....	1.00	.70
$Ca_3P_2O_8$ }	.10	.....	.....
Fe_2O_3 }		.....	.....
$CaSO_4.2H_2O$	.....	1.15	1.55
SiO_2 or sand	Trace.	1.36	.....
H_2O	.30	.82	1.46
Organic matter	.....	.37	.06
Insoluble	.05	.....	.....
	99.84	100.33	99.32

The reduced analyses, rejecting obvious impurities, are as follows:

Reduced analyses.

	1	2	3
SiO_2	Trace.		
Fe_2O_3	(?)		
$MgCO_3$	6.03	9.63	9.18
$CaCO_3$	93.87	88.42	88.84
$CaSO_4$		.93	1.26
$Ca_3P_2O_8$	.10	1.02	.72
	100.00	100.00	100.00

That these analyses fit well into our own series is evident.

In a worked specimen of *Corallium rubrum*, H. W. Nichols found 9.32 per cent of magnesium carbonate, not far from Bütschli's figure. In *Eunicea tourneforti* and *Plexaurella dichotoma*, both from the Bahamas, he found, respectively, 2.78 and 2.11 per cent. These percentages, however, are based on crude material; that is, without rejection of organic matter and water. They are, therefore, unavailable for comparison with our reduced analyses. Three similar analyses by G. Forchhammer[1] are also recorded, of *Tubipora musica*, *Corallium nobile* (= *C. rubrum*), and *Isis hippuris*, which gave, respectively, 3.83, 2.73, and 6.36 per cent of magnesium carbonate. These data lack sufficiently explicit details to admit of comparison with ours. Why his figure for the red coral is so low is not clear. The material taken for analysis must have been quite different from that used by Nichols or Bütschli. A still earlier analysis of red coral by Witting[2] gave 3.50 per cent of magnesium carbonate. The specimen analyzed, however, contained about 12 per cent of impurities.

If, now, we arrange the alcyonarians in the order of ascending magnesium carbonate, a remarkable relation connecting composition with temperature appears. *Heliopora*, being anomalous, is not included in the table. *Alcyonium carneum* is also excluded on account of its impurities. The three analyses by Anderson and Bütschli are, however, inserted. Localities and latitudes are abbreviated. The percentages of magnesium carbonate are from the reduced analyses, and those of calcium phosphate are also given.

Magnesium carbonate and calcium phosphate in alcyonarians.

Species.	Locality.	Latitude.	$Ca_3P_2O_8$.	$MgCO_3$.
Pleurocorallium johnsoni	Atlantic	25° 45′ N.	0.10	6.03
Primnoa reseda	Nova Scotia	42° 16′ N.	.83	6.18
Lepidisis caryophyllia	Off Nantucket	38° 33′ N.	Trace.	6.92
Pennatula aculeata	Atlantic	44° 47′ N.	3.12	7.71
Paramuricea borealis	Grand Banks		1.43	8.03
Paragorgia arborea	Nova Scotia		.56	9.05
Corallium rubrum	Mediterranean		.72	9.18
Alcyonium palmatum	Mediterranean?		1.02	9.63
Corallium elatior	Japan	33° N.	.40	11.56
Tubipora purpurea	Singapore	1° 20′ N.	Trace.	12.23
Muricea echinata	Cape San Lucas	22° 52′ N.	.83	12.28
Gorgonia acerosa	Bahamas	25° 5′ N.	3.64	12.52
Muricea humilis	Brazil	7°–8° S.	.59	12.64
Rhipidogorgia flabellum	Bermuda	32° N.	1.09	12.64
Xiphogorgia anceps	Florida	23° 30′ N.	1.96	13.04
Rhipidogorgia flabellum	Bermuda	25° N.	2.80	13.19
Gorgonia acerosa	Florida	23° 30′ N.	2.87	13.29
Gorgonia suffruticosa	Fiji		.47	13.43
Leptogorgia pulchra	Lower California	24° 16′ N.	8.27	13.71
Plexaurella grandiflora	Brazil		Trace.	13.79
Leptogorgia rigida	Cape San Lucas	22° 52′ N.	7.95	14.13
Ctenocella pectinata	Torres Strait	10° S.	.88	15.65
Phyllogorgia quercifolia	Brazil	3° 50′ N.	8.57	15.73

[1] Neues Jahrb., 1852, p. 854.

[2] Annales Chemie Pharmacie, vol. 1, p. 119, 1832.

Although records of temperature and depths are available for only a few of these alcyonarians, the suggested relation is clearly evident. The organisms from cold, northern waters or from very deep waters are low in magnesia, and those from warm regions are high. The same relation appears in our analyses of echinoderms and is unmistakable. It is not rigorously exact, but some apparent irregularities are due to impurities, such as sand and mud, which appear in the analyses as silica and sesquioxides. If these were rejected the percentage of magnesia would be raised. Variations are also to be expected because of cold or warm currents and different depths of water. Very deep water, even under the Equator, is always cold, whereas shallow bays farther north may be relatively warm. Possibly, also, the alcyonarians may form two or more distinct series that are not perfectly comparable in chemical composition. *Corallium* and *Tubipora*, for example, are compact forms, with little organic matter and lower magnesia than the genera with horny, organic axes, such as those whose names appear at the end of the table. It is also noteworthy that the highest proportions of calcium phosphate are commonly associated with a high content of magnesia.

HYDROIDS.

In the course of this investigation six analyses have been made of coralline hydroids belonging to the genera *Millepora* and *Distichopora*. The species and localities are as follows:

1. *Millepora alcicornis* Linné. Shoal water, Tortugas, Fla.
2. *Millepora alcicornis*. Bermuda.
3. *Millepora braziliensis* Verrill. Candeas, Pernambuco, Brazil.
4. *Distichopora nitida* Verrill. Micronesia, exact locality unknown.
5. *Distichopora coccinea* Gray. South Sea Islands, exact locality unknown.
6. *Distichopora sulcata* Pourtalès. Off Habana, Cuba; depth of water, 143 to 179 meters.

Analyses of millepores, etc.

	1	2	3	4	5	6
SiO_2	0.23	0.02	0.09	0.10	0.09	0.07
$(Al,Fe)_2O_3$	.10	.07	.06	.20	.07	.05
MgO	.43	.10	.59	.11	.12	.12
CaO	52.50	53.14	53.36	53.07	53.43	53.90
SO_3	.27	.04	1.03	.69	.65	.61
P_2O_4	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
Ignition	44.77	45.16	44.87	44.89	45.05	45.37
	98.30	98.53	100.00	99.06	99.41	100.12
CO_2 needed	41.57	41.85	42.01	41.44	41.76	42.15
Organic matter, etc	3.20	3.31	2.86	3.45	3.29	3.22

Reduced analyses.

	1	2	3	4	5	6
SiO_2	0.24	0.02	0.09	0.11	0.09	0.07
$(Al,Fe)_2O_3$	.11	.07	.06	.21	.07	.05
$MgCO_3$	.95	.22	1.28	.24	.26	.26
$CaCO_3$	98.22	99.63	96.77	98.22	98.43	98.56
$CaSO_4$	.48	.06	1.80	1.22	1.15	1.06
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00

A few partial analyses and one fairly complete analysis of millepores have already been published, which in all important particulars agree with ours. The coralline structures consist essentially of calcium carbonate, with minor impurities, and resemble chemically the true

corals. In two millepores from Bermuda A. G. Högbom[1] found respectively 95.86 and 94.39 per cent of calcium carbonate, with 0.41 and 0.97 of magnesium carbonate. In *Millepora alcicornis* from the Gulf Stream S. P. Sharples[2] found 97.45 per cent of calcium carbonate, 0.27 of calcium phosphate, 2.54 of organic matter and water, and only traces of iron and magnesia. B. Silliman, jr.,[3] in one analysis of the same species reported no magnesia, which evidently was not sought for. A single analysis of *M. braziliensis* by L. R. Lenox[4] gave the following composition:

$CaCO_3$	93.80
$MgCO_3$	2.14
$CaSO_4$	2.08
SiO_2	.03
$(Al,Fe)_2O_3$	.07
	98.12

It is interesting to note that the Brazilian species is the richest of all in magnesia, although it is poor in comparison with the echinoderms and alcyonarians. As reef builders the millepores contribute little to the coral rock but carbonate of lime.

In an analysis of *Millepora cervicornis*, by A. Damour,[5] 8.51 per cent of magnesium carbonate is reported. The name, however, belongs to a fossil species, and the specimen analyzed was at least partly fossilized. Its locality is given as Bréhat, Manche, France.

ANNELIDS.

The curious tubes formed by marine worms probably contribute little to the sediments. They are, however, of some interest in an investigation of this kind, and for that reason six analyses of them have been made, as follows:

1. *Filograna implexa* Berkeley (*Serpula complexa*). Scarborough, England.
2. *Protula tabularia* (Montagu) (*Serpula tabularia*). Locality unknown, probably British.
3. *Hydroides dianthus* Verrill. Vineyard Sound, Mass.
4. *Leodice polybranchia* Verrill. Off Marthas Vineyard, Mass.

5, 6. *Hyalinœcia artifex* Verrill. Off Marthas Vineyard, Mass., *Fish Hawk* station 1025; depth of water, 384 meters; bottom temperature, 7° C. Two analyses, of different samples; the tubes of this annelid, on ignition, gave an inorganic residue which fused to a white, porcelain-like mass.

Analyses of worm tubes.

	1	2	3	4	5	6
Insoluble in HCl	29.82	.....	.....	.....	.....	.....
SiO_2	1.12	0.75	15.45	28.05	0.20	0.24
$(Al,Fe)_2O_3$	.75	.41	1.30	2.33	.07	.01
MgO	.00	.14	3.58	4.40	8.57	8.17
CaO	35.98	50.89	39.11	5.12	5.35	5.24
SO_3	Trace.	.07	Trace.	6.06	3.47	4.33
P_2O_5	.29	Trace.	.22	6.43	20.72	20.32
Ignition	31.23	45.99	38.82	46.91	61.83	61.41
	99.19	98.25	98.48	99.30	100.21	99.72
CO_2 needed	28.00	39.95	34.46	.....	.....	.....
Organic matter, etc	3.23	6.04	4.36	.....	.....	.....

Tests for fluorine failed to show its presence in any of these tubes.

These analyses fall into two distinct groups, one low in sulphates and phosphates, the other unusually high. The first three are easily reducible to standard form if we reject the insoluble matter, the silica, and the sesquioxides, which represent inclusions of sand or mud. The reduced analyses then assume the following form:

[1] Neues Jahrb., 1894, Band 1, p. 262.
[2] Am. Jour. Sci., 3d ser., vol. 1, p. 168, 1871.
[3] Am. Jour. Sci. 2d ser., vol. 1, p. 189, 1846.
[4] Mus. Comp. Zool. Bull., vol. 44, p. 264, 1904.
[5] Compt. Rend., vol. 32, p. 253, 1851.

Reduced analyses of worm tubes.

	1	2	3
$MgCO_3$	0.00	0.32	9.72
$CaCO_3$	99.01	99.55	89.66
$CaSO_4$	Trace.	.13	Trace.
$Ca_3P_2O_8$	.99	Trace.	.62
	100.00	100.00	100.00

Two of these analyses resemble those of corals and mollusks; the third is n an alcyonarian or an echinoderm. In all three the organic matter is very low partial analyses by Forchhammer [1] are on record, which may be compared with t only magnesium carbonate was determined. These are—

Per c

Serpula sp. Mediterranean.....
Serpula triquetra. North Sea.....
Serpula filograna[2].....

The tubes of *Serpula* are evidently quite variable in composition, at least a magnesian content.

The tubes formed by *Leodice* and *Hyalinœcia*, being highly phosphatic, interpret chemically. The bases are insufficient to satisfy the acids if the phos assumed to represent the normal tribasic salts. Phosphorus may be present organic matter, and so, too, may a portion of the sulphur. Metaphosphates, p and acid orthophosphates are also possibly present, and between these alternativ to decide. Acid salts are, however, improbable, for when boiled in water the tul alkaline reactions. We prefer, therefore, to leave the reduction of analyses 4, 5, ance until more evidence can be obtained. In this direction an analysis of *O* Müller, by Schmiedeberg,[3] is suggestive. To the organic matter of the tube of (phin," he assigns the formula $C_{24}H_{43}NO_{18}$, and the tube itself he regards as a com of the composition

$$C_{24}H_{43}NO_{18} + CaHPO_4 + 4MgHPO_4 + 22H_2O.$$

The analyses given by Schmiedeberg are as follows:

Analyses of Onuphis tubicola.

	Entire tube.	Calcined ash.
Onuphin	38.48	P_2O_5
Water	24.07	CaO
P_2O_5	21.58	MgO
MgO	9.73	K
CaO	3.40	Na
H (acid), etc	2.74	SO_3, SiO_2, CO_2, and loss
	100.00	

In a general way this analysis of *Onuphis* resembles our analysis of *Hya* that the magnesia is much higher and the sulphates, if present, are insignificant will be noticed, moreover, that Schmiedeberg assumes the presence of acid ph interpretation of the data, which, as we have already stated, is improbable.

[1] Neues Jahrb., 1852, p. 854.

[2] In a later memoir (Philos. Trans., vol. 155, p. 203, 1865) Forchhammer gives the percentage of $MgCO_3$ in *Serpula filo* Which figure is correct?

[3] Zool. Sta. Naples Mitt., vol. 3, p. 373, 1882.

None of the analyses of the phosphatic worm tubes can be regarded as wholly satisfactory, but it is clear that these structures add phosphorus to the sediments. If they decay in contact with calcareous sediments, the final product would probably be a tribasic phosphate, and that is as far as we now need to go.

ECHINODERMS.

1. CRINOIDS.

In 1906 H. W. Nichols [1] published a number of partial analyses of marine invertebrates, and in a crinoid, *Metacrinus rotundus* from Japan, he found 11.72 per cent of magnesium carbonate. This analysis attracted the attention of Austin H. Clark, and at his request two other analyses of crinoids were made in the laboratory of the United States Geological Survey by Chase Palmer, who also found that they contained abundant magnesia. These analyses, which were published and discussed by Mr. Clark,[2] will be considered in detail later. They at once suggested that crinoids generally might be highly magnesian and so play an important part in the formation of magnesian limestones.

In order to settle this question Mr. Clark supplied us with 24 specimens of recent crinoids, representing 21 genera and covering a wide range of localities. These were analyzed by Mr. Wheeler, and the analyses confirmed the original supposition. All the specimens contained magnesium carbonate in notable proportions but varying in a most remarkable manner. The data obtained are in detail as follows, beginning with the list of the specimens studied:

1. *Ptilocrinus pinnatus* A. H. Clark. *Albatross* station 3342, off the Queen Charlotte Islands, British Columbia; latitude, 52° 39′ 30″ N.; longitude, 132° 38′ W.; depth of water, 2,858 meters; bottom temperature, 1.83° C. Mean of two analyses.

2. *Florometra asperrima* Clark. *Albatross* station 3070, off the coast of Washington; latitude, 47° 29′ 30″ N.; longitude, 125° 43′ W.; depth, 1,145 meters; bottom temperature, 3.28° C.

3. *Psathyrometra fragilis* Clark. *Albatross* station 5032, Yezo Strait, Japan; latitude, 44° 05′ N.; longitude, 145° 30′ E.; depth, 540–959 meters; bottom temperature, 1.61° C.

4. *Pentametrocrinus japonicus* P. H. Carpenter. *Albatross* station 5083, 34.5 miles off Omai Saki Light, Japan; latitude, 34° 04′ 20″ N.; longitude, 137° 57′ 30″ E.; depth, 1,123 meters; bottom temperature, 3.39° C.

5. *Capillaster multiradiata* Linné. *Albatross* station 5137, Philippine Islands near Jolo, 1.3 miles from Jolo Light; latitude, 6° 04′ 25″ N.; longitude, 120° 58′ 30″ E.; depth, 36 meters; no temperature record.

6. *Pachylometra patula* Carpenter. *Albatross* station 5036, Philippine Islands, North Balabac Strait, 15.5 miles from Balabac Light; latitude, 8° 06′ 40″ N.; longitude, 117° 18′ 45″ E.; depth, 104 meters; no temperature record.

7. *Catoptometra ophiura* Clark. Same locality as No. 6.

8. *Hypalocrinus naresianus* Carpenter. *Albatross* station 5424, Philippine Islands, 3.4 miles off Cagayan Island, Jolo Sea; latitude, 9° 37′ 05″ N.; longitude, 121° 12′ 37″ E.; depth, 612 meters; bottom temperature, 10.22° C.

9. *Parametra granulata* Clark. *Albatross* station 5536, Philippine Islands, between Negros and Siquijor, 11.8 miles from Apo Island; latitude, 9° 15′ 45″ N.; longitude, 123° 22′ E.; depth, 502 meters; bottom temperature, 11.95° C.

10. *Craspedometra anceps* Carpenter. *Albatross* station 5157, 3.3 miles from Tinakta Island, Tawi Tawi group, Sulu Archipelago; latitude, 5° 12′ 30″ N.; longitude, 119° 55′ 50″ E.; depth, 32 meters; no temperature record.

11. *Ptilometra mülleri* Clark. Sydney Harbor, New South Wales, Australia; latitude, 33° 15′ S.; longitude, 151° 12′ E., approximately.

12. *Hathrometra dentata* Say. *Fish Hawk* station 1033, off Marthas Vineyard, Mass.; latitude, 39° 56′ N.; longitude, 69° 24′ W.; depth, 329 meters; bottom temperature, about 7.8° C.

13. *Bythocrinus robustus* Clark. *Albatross* station 2401, Gulf of Mexico, southeast of Pensacola; latitude, 28° 38′ 30″ N.; longitude, 85° 52′ 30″ W.; depth, 255 meters; no temperature record.

14. *Crinometra concinna* Clark. *Albatross* station 2324, north of Cuba; latitude, 23° 10′ 35″ N.; longitude, 82° 20′ 24″ W.; depth, 59 meters; bottom temperature, 26.17° C.

15. *Isocrinus decorus* Wyville Thomson, stem. Off Habana, Cuba; latitude, 24° N.; longitude, 82° W.; approximately.

16. Same as No. 15, arms.

17. *Endoxocrinus parræ* Gervais, stem. Off Habana, Cuba.

18. Same as No. 17, arms.

19. *Tropiometra picta* Gay. Rio de Janeiro, Brazil; latitude, 25° 54′ S.; longitude, 44° W., approximately.

20. *Promachocrinus kerguelensis* Carpenter. Shores of the Antarctic Continent in the vicinity of Gaussberg; latitude, 67° S.; longitude, 90° E., approximately; depth, 350–400 meters; bottom temperature, −1.85° C.; salinity of water, 3.3 per cent.

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[1] Field Columbian Mus. Pub. 111, p. 31.

[2] U. S. Nat. Mus. Proc., vol. 39, p. 487, 1911.

21. *Anthometra adriani* Bell. Same locality as No. 20. Nos. 20 and 21 were collected by the C Expedition.

22. *Zygometra microdiscus* Bell. Aru Islands, near the western point of New Guinea; latitud

23. *Chlorometra rugosa* A. H. Clark. Near Rotti, Lesser Sunda Islands; latitude, 10° 39′ S.; lon depth, 520 meters.

The actual analyses are as follows. Sulphates were not determined beca was insufficient.

Analyses of crinoid skeletons.

	1	2	3	4
SiO_2	1.64	0.04	1.11	0.37
$(Al,Fe)_2O_3$	1.07	.34	1.01	.71
MgO	3.08	3.60	3.12	3.76
CaO	40.65	40.37	34.20	38.50
P_2O_5	.11	.21	Trace?	.40
Ignition	51.45	53.75	60.04	55.25
	98.00	98.36	99.48	98.99
CO_2 needed	35.23	35.48	31.37	34.01
Organic matter, etc	16.22	18.27	28.67	21.24

	7	8	9	10
SiO_2	0.04	0.07	0.40	0.15
$(Al,Fe)_2O_3$	.79	.09	.50	.19
MgO	4.64	4.44	4.48	5.13
CaO	40.75	45.86	41.79	42.77
P_2O_5	.33	Trace.	Trace.	.11
Ignition	51.80	48.32	51.44	50.28
	98.35	98.78	98.61	98.63
CO_2 needed	36.81	41.27	37.77	39.17
Organic matter, etc	14.99	7.05	13.67	11.11

	13	14	15	16
SiO_2	0.40	0.04	0.03	0.08
$(Al,Fe)_2O_3$	.31	.25	.07	.19
MgO	4.56	4.75	5.08	4.70
CaO	47.08	41.78	45.67	42.77
P_2O_5	Trace.	Trace.	Trace.	Trace
Ignition	47.17	50.33	47.54	50.59
	99.52	97.15	98.39	98.34
CO_2 needed	41.93	38.00	40.40	38.71
Organic matter, etc	5.24	12.33	7.14	11.88

	19	20	21
SiO_2	0.02	0.02	0.23
$(Al,Fe)_2O_3$	.35	.45	.37
MgO	4.51	3.02	3.27
CaO	39.57	40.68	42.49
P_2O_5	.10	Trace.	Trace
Ignition	53.64	54.53	52.22
	98.19	98.70	98.58
CO_2 needed	36.05	35.18	37.08
Organic matter, etc	17.59	19.35	15.14

The summation in most of these analyses is low. The deficiency is due mi or adherent sea salts, an inevitable impurity, as was proved in the analyses samples. In No. 15, 1.27 per cent of water-soluble salts was found, and in N cent. These additions raise the summations to 99.66 and 99.54 per cent, respe

The reduced analyses are as follows, rejecting organic matter and water and recalculating to 100 per cent:

Reduced analyses.

	1	2	3	4	5	6
SiO_2	2.01	0.05	1.57	0.48	0.21	0.14
$(Al,Fe)_2O_3$	1.31	.48	1.41	.91	.78	.74
$MgCO_3$	7.91	9.44	9.25	10.15	12.69	12.20
$CaCO_3$	88.48	89.45	87.77	87.34	86.32	85.81
$Ca_3P_2O_8$	.29	.58	Trace?	1.12	Trace.	1.11
	100.00	100.00	100.00	100.00	100.00	100.00

	7	8	9	10	11	12
SiO_2	0.05	0.08	0.47	0.24	0.21	5.73
$(Al,Fe)_2O_3$	.95	.10	.59	.22	.24	.56
$MgCO_3$	11.68	10.16	11.08	12.34	11.13	9.36
$CaCO_3$	86.46	89.66	87.86	86.93	87.94	83.47
$Ca_3P_2O_8$	.86	Trace.	Trace.	.27	.48	.88
	100.00	100.00	100.00	100.00	100.00	100.00

	13	14	15	16	17	18
SiO_2	0.42	0.05	0.03	0.10	0.04	0.17
$(Al,Fe)_2O_3$	.33	.30	.08	.21	.21	.29
$MgCO_3$	10.09	11.69	11.69	11.42	11.62	11.96
$CaCO_3$	87.16	87.96	88.20	88.27	88.13	87.58
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00

	19	20	21	22	23
SiO_2	0.02	0.02	0.28	0.05	0.06
$(Al,Fe)_2O_3$	.43	.57	.44	.62	.27
$MgCO_3$	11.17	7.86	8.23	13.37	9.87
$CaCO_3$	87.51	91.55	91.05	85.48	89.80
$Ca_3P_2O_8$	.27	Trace.	Trace.	.48	Trace.
	100.00	100.00	100.00	100.00	100.00

With these analyses the two made by Mr. Palmer may be advantageously compared, although they were not quite so elaborate. The data are as follows:

24. *Heliometra glacialis* var. *maxima*. Iwanai Bay, northeastern part of the Sea of Japan, latitude, 43° 01′ 40″ N.; depth, 315 meters; temperature, surface, 20.5° C., bottom, 1.5° C.

25. *Metacrinus rotundus*. Eastern Sea, off Kagoshima Gulf, southern Japan, latitude, 30° 58′ 30″ N.; depth, 278 meters; temperature, surface, 27.8° C., bottom, 13.3° C.

In No. 24, which contained much organic matter, Mr. Palmer found 2.68 per cent MgO (=5.61 $MgCO_3$) and 40.03 CaO (=71.48 $CaCO_3$). In No. 25, with no organic matter, he found 4.89 MgO (=10.29 $MgCO_3$) and 49.95 CaO (=89.19 $CaCO_3$). Assuming that the crinoid skeletons consist essentially of carbonates, and recalculating to 100 per cent, we have as the content of magnesium carbonate in these crinoids—

	Per cent.
24. *Heliometra glacialis* var. *maxima*	7.28
25. *Metacrinus rotundus*	10.34

These figures fit in well with the others and even by themselves suggest a relation between temperature and the magnesia content of crinoids. In the following table the entire series is

arranged in the order of ascending magnesium carbonate, with the accessory data as to latitude and locality abbreviated. In this table the two analyses of *Endoxocrinus* are averaged together, and so also are the two of *Isocrinus*.

Percentage of magnesium carbonate in crinoids.

Genus.	Locality.	Latitude.	Depth.	Temperature.	$MgCO_3$.
			Meters.	*°C.*	*Per cent.*
Heliometra	Northern Japan	43° N.	315	1.5	7.28
Promachocrinus	Antarctic	67° S.	375	−1.8	7.86
Ptilocrinus	British Columbia	52° 39′ N.	2,858	1.8	7.91
Anthometra	Antarctic	67° S.	375	−1.8	8.23
Psathyrometra	Northern Japan	44° N.	(?)	1.6	9.25
Hathrometra	Massachusetts	39° 56′ N.	329	7.8	9.36
Florometra	Washington	47° 29′ N.	1,145	3.3	9.44
Chlorometra	Rotti Island	10° 39′ S.	520	(?)	9.87
Bythocrinus	Gulf of Mexico	28° 38′ N.	255	(?)	10.09
Pentametrocrinus	Southern Japan	34° N.	1,128	3.4	10.15
Hypalocrinus	Philippine Islands	9° 37′ N.	612	10.2	10.16
Metacrinus	Southern Japan	30° 58′ N.	278	13.3	10.34
Parametra	Philippine Islands	9° 15′ N.	502	12	11.08
Ptilometra	Australia	33° 15′ S.	(?)	(?)	11.13
Isocrinus	Cuba	24° N.	(?)	(?)	11.56
Catoptometra	Philippine Islands	8° N.	104	(?)	11.68
Crinometra	Cuba	23° 10′ N.	59	26.2	11.69
Tropiometra	Brazil	25° 54′ S.	(?)	(?)	11.77
Endoxocrinus	Cuba	24° N.	(?)	(?)	11.79
Pachylometra	Philippine Islands	8° N.	1,044	(?)	12.20
Craspedometra	Philippine Islands	5° 12′ N.	32	(?)	12.34
Capillaster	Philippine Islands	6° N.	36	(?)	12.69
Zygometra	Aru Islands	5°–6° S.	(?)	(?)	13.37

The percentage of magnesium carbonate in *Chlorometra* is low for the latitude of the locality, but that is doubtless due to the depth of the water (520 meters) in which the crinoid lived. The probable temperature at that depth was between 7° and 10° C.

From the foregoing table it is perfectly clear that the proportion of magnesium carbonate in crinoids is in some way dependent on temperature. Temperature, however, is not entirely dependent on latitude. Depth of water has also a distinct influence. The crinoids from relatively shallow depths in the Tropics are highest in their magnesian content; those from the Antarctic and the far north are lowest. The proportion given for No. 12, from the coast of Massachusetts, is probably too low, for the specimen as analyzed contained over 6 per cent of silica and sesquioxides—evident impurities, due to adherent mud from which the delicate structure could not be wholly freed. If these are rejected, the magnesium carbonate is raised from 9.36 to 10 per cent, which gives the crinoid a better and more probable rating.

So far as we are aware such a peculiar relation between temperature and composition as is here recorded has not been previously observed. To recognize it is one thing; to account for it is not so easy. At first we supposed that it might possibly be due to a difference in the form of the more abundant carbonate—the less stable aragonite in the warm-water forms and calcite in the crinoids from colder regions. But tests by Meigen's reaction proved that the organisms were all calcitic, and so this supposition had to be abandoned.

Mr. A. H. Clark, who is an authority on the crinoids, informs us that the crinoids from warm regions have the most compact skeletons, the compactness being in general proportional to the temperature and to some extent dependent upon the size of the individual. *Heliometra*, for example, is the largest of the crinoids, its skeleton is one of the least compact, and its magnesian content is lowest among all the species examined. Structure as well as temperature seems to be correlated with the proportion of magnesia in the crinoids, but the chemical explanation of the facts is yet to be found. It may have connection with the gaseous content of sea water, carbon dioxide, for example, being more soluble in warm than in cold waters, but this is only a suggestion, which may or may not be fruitful. The same regularity of temperature also appears in our analyses of alcyonarians.

FOSSIL CRINOIDS.

In order to make this investigation more systematic it seemed desirable to analyze a number of fossil crinoids, so as to determine whether any definite and regular changes could be traced in passing from the recent to the ancient organisms. For the material studied we are indebted to the kindness of Mr. Frank Springer, who selected the material with great care so as to cover a range of horizons from the Lower Ordovician up to the Eocene. The 10 crinoids chosen are described in the list below, and the analyses which follow were made in the same way as those of the modern species.

1. *Pentacrinus decadactylus* D'Orbigny, stem. Eocene, Vincenza, Italy.
2. *Millericrinus mespiliformis* Goldfuss, stem. Upper Jurassic, Kelheim, Bavaria.
3. *Pentacrinus basaltiformis* Miller, stem. Middle Lias (Lower Jurassic) Breitenbach, Wurttemberg, Germany.
4. *Encrinus liliiformis* Lamarck, stem. Triassic, Braunschweig, Germany.
5. *Graphiocrinus magnificus* Miller and Gurley, complete crown. Pennsylvanian (upper Carboniferous), Kansas City, Mo.
6. *Dorycrinus unicornis* Owen and Shumard, calyx and stem. Lower part of Burlington limestone, Mississippian (lower Carboniferous), Burlington, Iowa.
7. *Megistocrinus nodosus* Barris, plates. Middle Devonian, Alpena, Mich.
8. *Eucalyptocrinus crassus*, plates. Silurian, western Tennessee.
9. Crinoid sp.?, stem. Trenton limestone, Middle Ordovician, Kirkfield, Canada.
10. *Diabolocrinus vesperalis* White, plates and stem. Lower Ordovician, Tennessee.

Analyses of fossil crinoids.

	1	2	3	4	5	6	7	8	9	10
SiO_2	0.99	2.84	1.55	0.24	3.07	6.92	10.39	29.11	2.56	4.07
$(Al,Fe)_2O_3$	2.64	.28	2.59	.43	2.18	.64	.87	1.73	.31	1.95
FeO	1.36	.00	.....	.00	1.32	.00	1.19	.27	.00	.88
MnO	.13	.00	.....	Trace.	.15	Trace.	.16	.04	Trace.	.04
MgO	.78	.38	.84	9.44	.78	.38	1.21	.58	.91	.79
CaO	51.22	53.68	51.78	43.40	50.10	51.20	46.57	37.43	53.87	50.42
P_2O_5	.00	Trace.	.09	Trace.	Trace.	Trace.	Trace.	.00	Trace.	Trace.
Loss on ignition	42.80	42.93	43.21	45.95	41.71	41.00	39.20	30.71	42.45	41.53
	99.92	100.11	100.06	99.46	99.32	100.14	99.59	99.87	100.10	99.68

Reduced analyses.

	1	2	3	4	5	6	7	8	9	10
SiO_2	1.00	2.85	1.57	0.24	3.11	6.94	10.48	29.30	2.55	4.10
$(Al,Fe)_2O_3$	2.66	.28	2.64	.44	2.22	.64	.88	1.74	.30	1.97
$FeCO_3$	2.21	.00	.....	.00	2.16	.00	1.94	.43	.00	1.42
$MnCO_3$	.21	.00	.....	Trace.	.24	Trace.	.26	.06	Trace.	.06
$MgCO_3$	1.66	.80	1.79	20.23	1.66	.80	2.56	1.23	1.90	1.67
$CaCO_3$	92.26	96.07	93.80	79.09	90.61	91.62	83.88	67.24	95.25	90.78
$Ca_3P_2O_8$	.00	Trace.	.20	Trace.	Trace.	Trace.	Trace.	.00	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

In some respects these analyses are unsatisfactory, for they show no regularities of any kind. In only one of them, No. 4, is there exhibited a concentration of magnesium carbonate; in the others the percentage of this constituent is very low. The reason for this decrease of magnesia is by no means clear. It is conceivable that the ancient crinoids may have been deficient in magnesia, but it is more probable that the loss is due to alteration, perhaps to the infiltration of calcium carbonate. Such a change would obviously lower the apparent proportion of magnesium carbonate. Several of the crinoids contain noteworthy quantities of ferrous carbonate and manganese—constituents which did not appear in the analyses of the modern species. In No. 8 there is a very strong silicification, 29.11 per cent; but the matrix of the specimen contained only 7.55 per cent of silica. Here the infiltration of the impurity

seems to be very clear. Some of the deficiencies in magnesia may have been caus and leaching, but calcium carbonate should then have been removed to a greate short, the fossil crinoids differ widely in composition from the still living species, irregular manner, and it is worth noting that in three analyses of fossil algæ reporte a similar decrease of magnesia appears. It would be easy to speculate on the these differences, but the conclusions so reached would not be entitled to much the recent crinoids are distinctly magnesian and that the proportion of magnesia in some way on temperature are the two positive results of this investigation.

2. SEA URCHINS.

Nine sea urchins, selected for us by Mr. Austin H. Clark, were analyzed. chosen were as follows:

1. *Strongylocentrotus dröbachiensis* O. F. Müller. Upernivik, Greenland, latitude 72° 48′ N.
2. *Strongylocentrotus fragilis* Jackson. *Albatross* station 2946, off southern California; latitude, longitude, 119° 30′ 45″ W.; depth of water, 274.5 meters; bottom temperature, 13.6° C.
3. *Echinarachnius parma* Lamarck. Coast of New England.
4. *Encope californica* Verrill. Galapagos Islands, on or near the Equator.
5. *Lytechinus anamesus* H. L. Clark. *Albatross* station 2938, off Wilmington, Cal.; latitude, 33° tude, 118° 08′ 30″ W.; depth, 86 meters; bottom temperature, 15° C.
6. *Loxechinus albus* Molina. Port Otway, Patagonia; latitude, about 46° or 47° S.
7. *Tetrapygus niger* Molina. Coast of Peru.
8. *Tretocidaris affinis* Philippi. *Albatross* stations 2316 and 2317, off Key West, Fla.; latitu longitude, 81° 47′ W.; depth, 85 meters; bottom temperature, 24° C.
9. *Heterocentrotus mammillatus* Linné. Low or Paumotu Archipelago, southern Pacific Ocean; 14° and 24° S.

The following analyses differ from those previously published[2] in being n and in the correction of certain errors of calculation:

Analyses of sea urchins.

	1	2	3	4	5
SiO_2	0.12	0.26	0.14	3.86	8.52
$(Al,Fe)_2O_3$	.34	.65	.27	5.03	3.01
MgO	2.58	2.68	2.97	4.75	3.04
CaO	47.34	41.08	49.17	43.42	37.92
SO_3	.20	1.15	.26	.28	.37
P_2O_5	Trace.	.39	.05	Trace.	.19
Ignition	48.53	52.21	45.74	43.01	45.38
	99.11	99.42	98.60	99.35	98.43
CO_2 needed	39.92	34.20	41.71	38.99	32.28
Organic matter, etc	8.61	18.01	4.03	4.02	13.10

Rejecting the very variable organic matter, etc., the reduced analyses assume form:

Reduced analyses.

	1	2	3	4	5
SiO_2	0.13	0.32	0.15	3.99	9.93
$(Al,Fe)_2O_3$	.37	.81	.29	5.20	3.51
$MgCO_3$	5.99	6.95	6.59	10.38	7.44
$CaCO_3$	93.13	88.44	92.39	79.94	77.91
$CaSO_4$	.38	2.42	.46	.49	.73
$Ca_3P_2O_8$	Trace.	1.06	.12	Trace.	.48
	100.00	100.00	100.00	100.00	100.00

[1] Neues Jahrb., 1894, Band 1, p. 252.
[2] Clarke, F. W., and Wheeler, W. C., The inorganic constituents of echinoderms: U. S. Geol. Survey Prof. Paper 90, p

Sea urchins Nos. 8 and 9, *Tretocidaris* and *Heterocentrotus*, must be considered separately from the others. No. 9, a giant form, was the subject of four analyses, the shell or test, the dental pyramid, the small white spines on the border of the peristome, and the large purplish-red spine. The large red spine analyzed was 15 centimeters long and weighed 13 grams.

Analyses of Heterocentrotus mammillatus.

	Shell.	Dental pyramid.	White spines.	Red spines.
SiO_2	0.02	0.02	0.05	0.05
$(Al,Fe)_2O_3$	.13	.08	.13	.26
MgO	5.21	5.50	3.74	4.47
CaO	43.60	46.02	48.26	47.72
SO_3	.61	.58	.29	.78
P_2O_5	Trace.	Trace.	Trace.	Trace.
Ignition	49.62	47.00	46.46	45.99
	99.19	99.20	98.93	99.27
CO_2 needed	39.66	42.89	41.77	41.49
Organic matter, etc	9.96	4.11	4.69	4.50

Reduced analyses.

SiO_2	0.02	0.02	0.05	0.05
$(Al,Fe)_2O_3$	.14	.09	.14	.28
$MgCO_3$	12.26	12.27	8.32	9.86
$CaCO_3$	86.42	86.57	90.97	88.43
$CaSO_4$	1.16	1.05	.52	1.38
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00

From these analyses we see that the inorganic constituents of *Heterocentrotus* are not uniformly distributed. The shell and teeth are alike and are rich in magnesium carbonate; the coarser spines are much less magnesian. The composition of the entire skeleton, if it can be called so, would probably be somewhere near that of the red spines alone, only a little higher in magnesia.

A similar example is offered by No. 8, *Tretocidaris*. In the specimen analyzed the shell and spines were taken separately, but the spines were dead when the urchin was collected. The analyses are as follows:

Analyses of Tretocidaris affinis.

Actual analyses.			Reduced analyses.		
	Shell.	Spines.		Shell.	Spines.
SiO_2	0.11	0.53	SiO_2	0.12	0.56
$(Al,Fe)_2O_3$	.15	.14	$(Al,Fe)_2O_3$	.16	.15
MgO	4.02	2.07	$MgCO_3$	9.30	4.63
CaO	45.80	49.79	$CaCO_3$	89.35	94.66
SO_3	.57	(?)	$CaSO_4$	1.07	(?)
P_2O_5	Trace.	Trace.	$Ca_3P_2O_8$	Trace.	Trace.
Ignition	48.32	46.28		100.00	100.00
	98.97	98.81			
CO_2 needed	40.09	41.40			
Organic matter, etc	8.23	4.88			

Here again the spines are lower in their content of magnesia than the shell.

In two of the analyses, Nos. 4 and 5, large percentages of silica and sesqu
These are due to inclosed or adherent sand and mud, which were visible in the
not readily removable. On rejecting these impurities and recalculating to 10(
percentages of magnesium carbonate became 11.43 and 8.59, respectively. Simila
the other analyses are negligible. After making these corrections and assuming t
found for the shell rather than the spines in Nos. 8 and 9, the next table has be
If, however, the composition of the entire *Heterocentrotus* should be taken, it
places with *Encope*.

Percentage of magnesium carbonate in sea urchins.

	Locality.	Latitude.	Depth.	Te t
			Meters.	
Strongylocentrotus dröbachiensis	Greenland	72° 48′ W.	(?)	
Tetrapygus	Peru	(?)	(?)	
Echinarachnius	New England	42° 45′ N.	(?)	
Strongylocentrotus fragilis	California	33° 58′ N.	2,745	
Loxechinus	Patagonia	46° 47′ S.	(?)	
Lytechinus	California	33° 35′ N.	85	
Tretocidaris	Key West	24° 25′ N.	85	
Encope	Paumotu	14° 24′ S.	(?)	
Heterocentrotus	Galapagos	Equator	(?)	

These figures, like those for the crinoids, seem to show a regular variation i
at least so far as temperatures have been determined or can be inferred. The se
cold regions are relatively low in magnesia; those from the Tropics are high. Th
one apparent exception—the urchin from Peru. This abnormality is probably
Humboldt current which flows northward from the Antarctic Ocean. A larger se
of sea urchins, with more details as to depth of water and temperatures, is much t

Two published analyses of sea urchins are worth reproducing. They are:

1. *Echinus (Strongylocentrotus?) dröbachiensis.* North Sea; analysis by L. Schmelck. Norske
No. 28, p. 129, 1901.

2. *Echinus esculentus.* Locality not stated, probably Mediterranean; analysis by O. Bütschli.
Göttingen Abh., No. 3, 1908.

Older analyses of sea urchins.

Actual analyses.			Reduced analyses.	
	1	2		
SiO_2	Trace.	0.04	SiO_2	
Al_2O_3	Trace.	.....	Al_2O_3	
Fe_2O_3	0.30	.....	Fe_2O_3	
$CaCO_3$	77.75	86.40	$MgCO_3$	
$MgCO_3$	5.30	8.53	$CaCO_3$	
P_2O_5	Trace.	.....	$CaSO_4$	
Phosphate	.....	.08	$Ca_3P_2O_8$	
$CaSO_4$	Trace.	.....		
$CaSO_4.2H_2O$	.....	1.70		
H_2O	.....	2.45		
Organic matter	16.33	.03		
	99.68	99.23		

Although different in minor details these analyses are fairly comparable w
urchin analyzed by Schmelck was from the far north, and its composition is ve
our specimen from Greenland. Bütschli's sea urchin is doubtless from warmer w
the higher figure for magnesium carbonate.

3. STARFISHES AND BRITTLE STARS.

Eleven starfishes, including brittle stars, were analyzed, as follows:

1. *Asterias vulgaris* Packard. Eastport, Maine; latitude, 44° 55′ N.; longitude, 67° 00′ W.
2. *Asterias tanneri* Verrill. *Albatross* station 2309; latitude, 35° 43′ 30″ N.; longitude, 74° 52′ W.; depth, 102 meters; bottom temperature not given.
3. *Asterina miniata* Brandt. Pacific Grove, Cal.; latitude, 36° 36′ N.; longitude, 121° 55′ W.
4. *Leptasterias compta* Stimpson. *Albatross* station 2250; latitude, 40° 17′ 15″ N.; longitude, 69° 51′ 45″ W.; depth, 86 meters; bottom temperature, 10.8° C.
5. *Benthopecten spinosus* Verrill. *Albatross* station 2568; latitude, 39° 15′ 00″ N.; longitude, 68° 08′ 00″ W.; depth, 3,249 meters; bottom temperature, 2.7° C.
6. *Luidia clathrata* Say. Near Charleston, S. C.; latitude, 32° 47′ N.; longitude, 79° 57′ W.; depth, between 2 and 22 meters.
7. *Acanthaster planci* Linné. Palmyra Island, in the Pacific Ocean, west of south from Hawaii; latitude, 5° 49′ N.
8. *Gorgonocephalus arcticus* Gray. Off Cape Cod, Mass.; about latitude 42° N.
9. *Gorgonocephalus caryi* Lyman. Alaska.
10. *Ophioglypha sarsii* Lütken. *Albatross* station 2176; latitude, 39° 32′ 30″ N.; longitude, 72° 21′ 30″ W.; depth, 553 meters; bottom temperature, 5° C.
11. *Ophioderma cinereum* Müller and Troschel. Ensenada Honda, Culebra Island, east of Porto Rico; latitude, 18° 20′ N., approximately.

The last locality is in or on the edge of the equatorial current. The *Albatross* stations were all fixed on cruises between Cape Hatteras and Nantucket. The analyses are as follows:

Analyses of starfishes.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	0.45	0.79	0.03	1.21	2.06	0.27	0.19	1.77	1.08	0.98	0.21
$(Al,Fe)_2O_3$	.21	.55	.20	.48	.79	.36	.14	.62	.72	.53	.09
MgO	2.59	3.83	3.98	3.05	3.93	4.89	4.36	3.36	2.82	3.99	5.80
CaO	35.71	38.51	36.85	30.35	40.54	41.30	33.18	36.13	29.80	42.14	41.32
SO_3	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)	.69	(?)	.16
P_2O_5	.07	.24	.14	.13	.11	.14	.07	.22	.32	.29	.07
Ignition	60.18	54.89	57.64	63.91	51.66	52.03	62.07	55.72	63.37	50.95	51.58
	99.21	98.81	98.84	99.13	99.09	98.99	100.01	97.82	98.80	98.88	99.23
CO_2 needed	30.84	34.30	33.05	27.08	35.94	37.70	30.81	31.65	25.85	37.29	38.69
Organic matter, etc.	29.34	20.59	24.59	36.83	15.72	14.33	31.26	24.07	37.52	13.66	12.89

Reduced analyses.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	0.64	1.01	0.03	1.94	2.47	0.32	0.27	2.39	1.76	1.15	0.24
$(Al,Fe)_2O_3$	.30	.70	.27	.77	.94	.42	.20	.84	1.17	.62	.11
$MgCO_3$	7.79	10.28	11.24	10.27	9.88	12.13	13.33	9.53	9.66	9.84	14.08
$CaCO_3$	91.06	87.44	88.06	86.57	86.42	86.77	85.99	86.60	84.36	87.65	85.09
$CaSO_4$	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)	1.91	(?)	.30
$Ca_3P_2O_8$	.21	.57	.40	.45	.29	.36	.21	.64	1.14	.74	.18
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

In the following table the analyses are arranged in the order of ascen carbonate, like those of the sea urchins and crinoids:

Percentage of magnesium carbonate in starfishes.

Species.	Locality.	Latitude.	Depth.
			Meters.
Asterias vulgaris	Eastport	44° 55′ N.	(?)
Gorgonocephalus arcticus	Cape Cod	42° ± N.	(?)
Gorgonocephalus caryi	Alaska	(?)	(?)
Ophioglypha sarsii	Station 2176	39° 32′ N.	553
Benthopecten spinosus	Station 2568	39° 15′ N.	3,249
Leptasterias compta	Station 2250	40° 17′ N.	86
Asterias tanneri	Station 2309	35° 43′ N.	102
Asterina miniata	California	36° 38′ N.	(?)
Luidia clathrata	Charleston	32° 47′ N.	(?)
Acanthaster planci	Palmyra Island	5° 49′ N.	(?)
Ophioderma cinereum	Culebra	18° 20′ N.	(?)

Here again we meet the same coordination of temperature with conter carbonate that was noted among the other echinoderms. The starfishes from lowest in magnesium carbonate; those from warm regions run higher. Wheth coordination is general or not is still an open question, for several analyses by forms from the North Sea are not easy to explain. Schmelck's data are as fol

1. *Astrophyton;* an ophiuran. Station 37; latitude, 78° 48′ N.; longitude, 8° 57′ E.; depth bottom temperature, 1.1° C.

2. *Arcaster tenuispinus.* Station 10; latitude, 61° 41′ N.; longitude, 3° 19′ E.; depth, 402 perature, 6° C.

3. *Arcaster tenuispinus.* Station 25; latitude, 63° 10′ N.; longitude, 5° 25′ E.; depth, 179 perature, 6.9° C.

4. *Astropecten andromeda.* Station 10; details under No. 2.

Schmelck's analyses of starfishes.

	1	2
SiO	Trace.	Trace.
Al_2O_3	Trace.	Trace.
Fe_2O_3	0.31	0.31
$MgCO_3$	7.60	9.36
$CaCO_3$	74.82	74.11
$CaSO_4$	.71	(?)
P_2O_5	Trace.	Trace.
Organic matter	17.57	16.23
	101.01	100.00

Schmelck's analyses reduced.

	1	2
SiO_2	Trace.	Trace.
Al_2O_3	Trace.	Trace.
Fe_2O_3	0.37	0.36
$MgCO_3$	9.11	11.18
$CaCO_3$	89.67	88.46
$CaSO_4$	.85	(?)
$Ca_3P_2O_8$	Trace.	Trace.
	100.00	100.00

[1] Norske Nordhavs Exped. No. 28, p. 129, 1901.

2 and 4 of this group of analyses represent the same locality and temperature. If ɜive and surely extraneous silica in No. 4 is rejected and the analyses are recalculated r cent the figure for magnesium carbonate becomes 11.41, nearly that for No. 2. All ntages given for magnesium carbonate are higher than the temperatures would lead ɔct, but they still fall far below the three highest in our table. A general tendency to as regards temperature is evident, but it is perhaps not invariable. More data relarfishes are much to be desired.

4. HOLOTHURIANS.

ɔugh the holothurians are of slight importance as contributors to the marine sediments, desirable to compare a few of them with the other echinoderms. Four holothurians efore analyzed, but their organic matter was so vastly in excess of their hard parts ınalyses, with one exception, are far from satisfactory. However, the data, which are ıut some significance, are as follows:

thuria floridana Pourtalès. Fajardo, Porto Rico.
:maria frondosa (Gunnerus). A northern cold-water species, precise locality unknown.
hostoma intermedium Ludwig. Off Cersos Island, Cal. Weight of sample, 0.2204 gram.
hostoma intermedium. *Albatross* station 3307, in Bering Sea; latitude, 56° 12′ N.; longitude, 172° 55′ W.; ter, 130 meters; bottom temperature, 3.3° C. Weight of sample, 0.1175 gram.

Analyses of holothurians.

	1	2	3	4
.....	0.08	0.27	5.56	6.93
.....	.18	.25	8.40	6.31
.....	3.48	.41	1.81	1.36
.....	25.19	1.10	4.91	1.44
.....	Trace.	.85	3.15	1.86
.....	.74	1.29	(?)	(?)
.....	69.93	95.71	76.71	82.21
	99.60	99.88	100.54	100.11
.....	23.21	(?)	(?)	(?)
ıtter, etc.....	46.72	(?)	(?)	(?)

ɔ. 2, 0.31 per cent of matter soluble in water was found, which raises the summation

ɹese analyses only the first is reducible with any certainty to standard form. The perɔmposition of the inorganic portion of the specimen then becomes—

.....	0.15
$e)_2O_3$	.34
$)_3$.....	13.84
ɜ.....	83.29
.....	2.38
O_8	Trace.
	100.00

is very near the analysis of the starfish.from Culebra Island, which is not far from the this holothurian. The coincidence is very striking.

e specimen represented by analysis 2 the proportion of inorganic matter was so small results could hardly be obtained. The other two analyses were also made with altodequate material. These analyses, however, show that the small inorganic portions ɔthurians are relatively rich in phosphatic matter and in magnesia. The difficulties ing them intelligently are like those of discussing the worm tubes and the axes of ıns. In *Trochostoma* there are brown spots, which were already known to be phosɜhough quantitative analyses of them seem to be lacking. The true character of such

bodies can be determined only by an elaborate investigation upon abundant material, a task which lies outside of our main problem.

Two analyses of holothurians are already on record, as follows:

1. *Stichopus regalis.* Locality not stated; analysis by O. Bütschli, K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.
2. Ash of the epidermis ("lederhaut") of a large holothurian, species and locality not stated; analysis by Hilger. Pflüger's Archiv. f. Physiologie, vol. 10, p. 212, 1875.

Old analyses of holothurians.

	1	2		1	2
Na_2SO_4	.....	4.47	$FeCO_3$	.....	1.02
NaCl	.....	.83	H_2O	3.67	.....
$CaCO_3$	81.54	78.96	Sand	3.23	.....
$MgCO_3$	8.10	12.10	SiO_2	.....	.57
$CaSO_4$	.....	1.04	Organic	1.03	.....
$CaSO_4.2H_2O$	2.09	.....			
$Ca_3P_2O_8$	.....	.96		99.66	99.95

These analyses, together with ours of *Holothuria*, show that the hard parts of these animals, like those of the other echinoderms, are distinctly magnesian. Although definite data are wanting, it seems probable that Hilger's specimen came from warmer water than that analyzed by Bütschli. The sodium salts are of course extraneous.

5. SUMMARY.

From the evidence now available it seems almost certain that the inorganic constituents of any echinoderm will have the composition of a moderately magnesian limestone. There may be exceptions, but none has yet been found. The four tables—for crinoids, sea urchins, starfishes, and holothurians—all tell the same story, and with remarkable unanimity. Furthermore, the proportion of magnesium carbonate appears to be a function of temperature, the organisms from warm waters being richer in it than those from cold waters. The exceptions to this rule are few and may be only apparent, for cold or warm currents and varying depths of water account for nearly all irregularities. Schmelck's analyses of starfishes from the North Sea are the only ones so far which are troublesome to explain.

The sea urchins seem to be a little poorer in magnesia than either of the other groups, but the analyses are fewer and therefore less conclusive. Silica and sesquioxides are probably altogether extraneous, although it is possible that small quantities of them may really belong to the organisms. In phosphate of lime the starfishes are richest, and all the specimens analyzed contain it in small amounts. Whether it is an essential constituent or not is uncertain. As shown by Meigen's reaction, all the echinoderms studied are calcitic, and no evidence of aragonite in them was found.

The temperature relations shown by the analyses offer an interesting biological problem, with which we can not undertake to cope. It is not due to differences of composition in the solid matter of sea water, for that is practically uniform the world over. In all the great oceans, and even in minor bodies of water like the Mediterranean, the Baltic, and the Black seas, the proportion of magnesia to lime is very nearly if not actually constant. In gaseous contents and especially in carbon dioxide the waters vary; the gases being more soluble in cold than in warm water. Whether this fact has any relation to the phenomenon under discussion we can not attempt to say. We can only report the facts and leave their biological discussion to others.

BRYOZOA.

Nine Bryozoa have been analyzed in the course of this research, as follows:

. *Schizoporella unicornis* Johnston. Vineyard Sound, Mass.; depth of water, 15.5 meters; bottom temperature, C.

. *Schizoporella unicornis* Johnston. Between Johns Pass and Pass a Grille, Fla.

. *Microporella grisea* Lamouroux. Australia.

. *Cellepora incrassata* Lamarck. Northeast part of the Grand Banks.

. *Flustra membranacea truncata* Smith. St. Paul Island, Pribilof group, Alaska; latitude, 57° N.; longitude, W. Only 0.1165 gram available for analysis.

. *Lepralia pallasiana* Möller. Off Gloucester, Mass. A thin coating on a granite pebble; weight of organism, 3 gram.

. *Catenicella margaritacea* Busk. Australia.

. *Bugula turrita* Desor. Georges Bank, off coast of Massachusetts; *Albatross* station 2578; latitude, 41° 20′ 30″ N., tude, 68° 34′ 30″ W.; depth of water, 67.7 meters; bottom temperature, 12.3° C.

. *Bugula neritina* Linné. Florida.

The actual analyses are as follows:

Analyses of Bryozoa.

	1	2	3	4	5	6	7	8	9
.....	1.65	2.49	0.17	0.19	3.00	4.78	0.95	8.77	6.31
$e)_2O_3$.....	.29	.37	.11	.19		.13	.41	1.18	.75
.....	.28	2.04	.49	2.74	2.06	2.32	3.50	2.55	2.57
.....	50.90	48.17	50.83	49.36	30.81	43.08	40.83	20.45	19.69
.....	Trace.	Trace.	.10	Trace.	.09	.11	.16	.38	.60
.....	.73	.77	.79	.98	(?)	(?)	1.00	1.47	2.43
ion.....	45.64	45.70	46.80	46.03	61.45	.....	52.66	61.51	59.47
	99.49	99.54	99.29	99.49	97.41	50.42	99.51	96.31	91.82
ieeded.....	39.92	40.16	39.94	41.26	26.39	36.29	35.23	17.69	16.41
ıic matter, etc.....	5.72	5.54	6.86	5.06	35.06	13.29	17.43	43.82	43.06

Reduced analyses.

	1	2	3	4	5	6	7	8	9
.....	1.77	2.66	0.18	0.20	4.82	5.52	1.15	16.71	12.94
$e)_2O_3$.....	.31	.39	.12	.20		.15	.50	2.25	1.54
$)_3$.....	.63	4.58	1.11	6.07	6.94	5.62	8.96	10.19	11.08
$_3$.....	95.97	90.97	96.90	91.77	87.92	88.44	86.89	64.51	63.29
O_3.....	Trace.	Trace.	.24	Trace.	.32	.27	.43	1.58	2.68
₄.....	1.32	1.40	1.45	1.76	(?)	($)	2.07	4.76	8.47
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Bryozoa Nos. 1 to 5 were massive coralline forms and were easily handled. No. 6, *alia*, was an incrustation upon a pebble, from which it could not well be separated mechany. The entire specimen was therefore weighed, the bryozoan was then dissolved by hydroric acid, and the pebble was weighed again. The solution only was available for analysis, the usual loss on ignition could not be determined but was necessarily taken by difference. ı an analysis is obviously unsatisfactory but not entirely worthless. Bryozoa Nos. 7 to ıre delicate mossy or fernlike organisms, and the poor summations of the last two indicate presence of undetermined saline matter. The high silica in them is evidently due to ısed sand. If silica and sesquioxides are rejected and the remainders recalculated to 100 ːent the percentages of magnesium carbonate become 12.51 and 12.95, respectively. The nesia, however, shows no such regularity as regards temperature as appears in our series of ɔnarians and echinoderms. The difference between the magnesian content of the two

specimens of *Schizoporella* is very striking. What this difference may signify is yet to be determined.

Several other analyses of Bryozoa, complete or partial, are recorded in the literature. Two of them, fairly complete, were made by A. Schwager for J. Walther.[1] They are as follows, both specimens being from the Bay of Naples:

1. *Eschara foliacea.*
2. *Lepralia* sp.

Schwager's analyses of Bryozoa.

	Actual analyses.			Reduced analyses.	
	1	2		1	2
SiO_2	0.29	2.39	SiO_2	0.31	2.58
$(Al,Fe)_2O_3$	.32	1.47	$(Al,Fe)_2O_3$	.34	1.58
MgO	1.20	2.22	$MgCO_3$	2.71	5.02
CaO	50.12	47.18	$CaCO_3$	96.64	90.82
CO_2	41.06	39.51		100.00	100.00
Organic matter+H_2O	6.88	7.53			
	99.87	100.00			

The reduced analyses were computed by us from Schwager's data.

In *Flustra foliacea* from California H. W. Nichols[2] found 1.23 per cent of magnesium carbonate, and in a bryozoan from Bermuda 5.35 per cent. Several similar determinations by G. Forchhammer[3] on other Bryozoa gave less than 0.6 per cent. The other constituents of the organisms were not determined, and the figures given for magnesium carbonate therefore have little present value.

From the evidence now at hand no broad general conclusions can be drawn. That the magnesian content of the Bryozoa varies widely, however, is clear, being lowest in the compact coralline forms and highest in the fernlike varieties. Even this conclusion needs to be verified by a much larger series of analyses.

BRACHIOPODS.

A few analyses of brachiopod shells already on record show that they fall into two chemically distinct groups—one calcareous, the other highly phosphatic. This conclusion is supported and emphasized by the new data obtained by us, which also bring out some minor peculiarities that seem not to have been previously observed. For our material we are indebted to Dr. W. H. Dall, who selected typical specimens from among the duplicates in the United States National Museum. First in order come five brachiopods representing as many genera in the calcareous group. The analyses are as follows:

1. *Terebratula cubensis* Pourtalès. Coast of Florida.
2. *Terebratulina septentrionalis* Gray. Eastport, Maine.
3. *Laqueus californicus* Koch. Esteros Bay, Cal.
4. *Rhynchonella psittacea* Gmelin. Shetland Islands.
5. *Crania anomala* Muller. Coast of Norway.

[1] Deutsch. geol. Gesell. Zeitschr., p. 338, 1885. [2] Field Columbian Mus. Pub. 111, p. 31, 1906. [3] Neues Jahrb., p. 854, 1852.

Analyses of calcareous brachiopods.

	1	2	3	4	5
SiO_2	0.06	0.50	0.18	0.14	0.21
$(Al,Fe)_2O_3$	.04	.14	.47	.23	.26
MgO	.44	.62	.32	.23	3.90
CaO	54.96	51.79	54.48	53.76	48.67
SO_3	.21	.66	.21	.31	.97
P_2O_5	Trace.	Trace.	Trace.	.17	.25
Loss on ignition	44.35	45.28	44.46	44.81	45.38
	100.06	98.99	100.12	99.65	99.64
CO_2 needed	43.42	40.55	42.91	42.16	40.88
Organic matter, etc	.93	4.73	1.55	2.65	3.52

Rejecting organic matter and recalculating to 100 per cent, the analyses assume the following rational form:

Reduced analyses.

	1	2	3	4	5
SiO_2	0.06	0.52	0.18	0.15	0.22
$(Al,Fe)_2O_3$	.04	.15	.48	.23	.27
$MgCO_3$	.93	1.37	.68	.49	8.63
$CaCO_3$	98.61	96.78	98.30	98.20	88.59
$CaSO_4$	.36	1.18	.36	.55	1.72
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	.38	.57
	100.00	100.00	100.00	100.00	100.00

For comparison the following analyses of calcareous brachiopods, made elsewhere, are significant:

6. *Terebratula* sp. Collected by Pourtalès between Florida and Cuba; S. P. Sharples, analyst.[1]
7. *Terebratulina caput serpentis*. Locality not given; F. Kunckell, analyst.[2]
8. *Crania anomala* Müller. Locality not given; Kunckell, analyst.
9. *Waldheimia cranium* Müller. Locality not given; Kunckell, analyst.
10. *Waldheimia cranium*. Collected by the Norwegian North Sea Expedition, station 255; latitude, 68° 12′ N.; longitude, 15° 40′ E.; depth, 624 meters; bottom temperature, 6.5° C.
11. *Waldheimia cranium*. Lofoten Islands. Analyses 10 and 11 by L. Schmelck.[3]

Older analyses of calcareous brachiopods.

	6	7	8	9	10	11
SiO_2					0.60	(?)
Fe_2O_3	Trace.				.40	0.15
$MgCO_3$	Trace.	1.05	3.4		1.20	1.40
$CaCO_3$	98.39	94.6	87.8	96.2	96.20	95.98
$CaSO_4$		2.4	2.15	.9	.85	(?)
$Ca_3P_2O_8$	.61		.28	.18		
SrO						Trace.
CaO				.3		
MgO			1.8	.6		
P_2O_5					Trace.	.12
Organic matter	1.00	2.55	4.3	2.0	1.24	1.99
	100.00	100.00	99.73	100.18	100.49	99.64

With these analyses ours agree in a broad, general way, although the older ones vary much as regards completeness. Kunckell's analyses, showing free lime and magnesia, are

[1] Am. Jour. Sci., 3d ser., vol. 1, p. 168, 1871.
[2] Jour. prakt. Chemie, 2d ser., vol. 59, p. 102, 1899.
[3] Norske Nordhavs Exped., No. 28, p. 129, 1901.

suspicious, but only in this detail; otherwise they have confirmatory value. All the analyses show that brachiopods of this group have shells in which calcium carbonate is the principal constituent and that the proportion of organic matter is low. The only aberrant one is *Crania*, which is noteworthy on account of its high percentage of magnesia. In this respect, Kunckell's analysis, if recalculated to a common basis, agrees approximately with ours. *Rhynchonella* is also interesting for the reason that an analysis by Hilger of shells supposed to belong to this genus indicates that they are phosphatic and practically identical in composition with those of *Lingula*. The authenticity of Hilger's material is questionable, and his analysis will not be reproduced here.

Four analyses of shells of phosphatic brachiopods have been made by us. As these shells contain a large amount of organic matter, which possibly varies with the age or maturity of the animal, we prefer to report our results, as others before us have done, in proximate rather than ultimate form. The analyses are as follows:

1. *Lingula anatina* Gmelin. Coast of Higo Province, Japan. Organic matter, rejected, 40 per cent.
2. *Lingula anatina*. Iloilo, Philippine Islands. Organic matter, rejected, 39.5 per cent.
3. *Discinisca lamellosa* Broderip. Coast of Peru. Organic matter, rejected, 25 per cent.
4. *Glottidia* (formerly *Lingula*) *pyramidata* Stimpson, coast of North Carolina. Organic matter, about 37 per cent; analysis incomplete for lack of sufficient material.

Analyses of phosphatic brachiopods.

	1	2	2	4
SiO_2	0.91	0.50	0.85	0.49
$(Al,Fe)_2O_3$	.54	.29	.58	1.16
$MgCO_3$	2.70	.79	6.68	1.71
$CaCO_3$	1.18	4.25	8.35	(?)
$CaSO_4$	2.93	4.18	8.37	(?)
$Ca_3P_2O_8$	91.74	89.99	75.17	74.73
	100.00	100.00	100.00	.....

These analyses are noteworthy on account of the unusual proportion of calcium sulphate reported in them. *Discinisca* is especially remarkable in this respect and also in its percentage of magnesium carbonate. Small amounts of sulphates have been found in many mollusks and corals as well as in the calcareous brachiopods but in nothing like the proportion given here. A new analysis of *Discinisca* made upon fresh material is much to be desired.

In the older analyses of this group the sulphate seems to have been ignored, or at least to have escaped attention. The figures are as follows:

5. *Lingula ovalis*. Hawaiian Islands; T. S. Hunt, analyst.[1]
6, 7. *Lingula ovalis*. Locality not given; A. Hilger, analyst.[2]
8. *Lingula anatina*. S. Clōez, analyst;[3] recalculated to 100 per cent after rejecting 42.6 per cent of organic matter.

Older analyses of phosphatic brachiopods.

	5	6	7	8
SiO_2	.....	0.18	0.17	Trace.
$MgCO_3$	.....	2.94	3.13	.....
$CaCO_3$	11.75	10.76	10.86	12.19
$Ca_3P_2O_8$	85.79	84.94	85.24	77.17
$Mg_3P_2O_8$	.....	.....	.....	7.03
$FePO_4$	.....	.77	.76	3.61
MgO?	2.80	.....	.....	.....
	100.34	99.59	100.00	100.00

[1] Logan, W. E., and Hunt, T. S., Am. Jour. Sci., 2d ser., vol. 17, p. 237, 1854.
[2] Jour. prakt. Chemie, vol. 102, p. 418, 1867.
[3] Jahresb. Chemie, 1859, p. 642; from L'Institut, 1859, p. 240.

The relatively high figures for calcium carbonate shown in this table are doubtless due to the neglect to determine sulphate. The analysis by Clõez differs from the others principally in form—that is, in its mode of calculation. If the phosphoric oxide in it is assigned entirely to the lime, then the proportion of calcium phosphate becomes 88.6 per cent, which is well in line with the other figures. The amount of calcium carbonate would be correspondingly reduced.

The brachiopods, as stated at the beginning of this section, fall into two distinct groups; the shells of one consist mainly of calcium carbonate, with little organic matter, and those of the other predominatingly of calcium phosphate, with much organic matter. The two groups, although they may be alike structurally, are physiologically quite dissimilar, the chemical reactions involved in building the shells being of two different orders. Such a distinction ought to be significant to biologists and it is for them to determine what it means. Geologically, however, we can see that the phosphatic brachiopods have probably played some part in the formation of phosphatic sediments, a function which is shared by vertebrate animals and some crustaceans.

MOLLUSKS.

Numerous analyses of molluscan shells have been published, and they show remarkable uniformity of composition. It has nevertheless seemed desirable to make a liberal series of new analyses, which are best classified into groups. Sulphates were not determined, except in four analyses.

1. PELECYPODS.

The pelecypod shells analyzed are as follows:

1. *Astarte crenata* Gray. Off Marthas Vineyard, Mass.; depth of water, 668 meters; bottom temperature, 72° C.
2. *Callista convexa* Say. Vineyard Sound, Mass.
3. *Macoma sabulosa* Spengler. Massachusetts Bay; depth, 825 meters; bottom temperature, 5.5° C.
4. *Pecten dislocatus* Say. Charlotte Harbor, Fla.
5. *Pecten ventricosus* Sowerby. Head of Concepcion Bay, Lower California.
6. *Venericardia ventricosa* Gould. Off Point Concepcion, southern California; latitude, 34° 25′ N.; depth, 447 meters; bottom temperature, 7.3° C.
7. *Cardium substriatum* Conrad. Long Beach, Cal.
8. *Calyptogena pacifica* Dall. Clarence Strait, Alaska; latitude, 55° 46′ N.; depth, 589 meters; bottom temperature, 5.8° C.
9. *Nucula expanser* Hancock. North of Bering Strait.
10. *Acila mirabilis* Adams and Reeve. Japan Sea, off the coast of Chosen (Korea); depth, 128 meters; bottom temperature, 16° C.
11. *Placuna orbicularis* Retzius. Off Luzon, Philippine Islands.

Analyses of pelecypod shells.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	0.25	0.18	0.29	0.31	0.14	0.12	0.11	0.08	0.33	0.09	0.00
$(Al,Fe)_2O_3$	.08	.11	.22	.08	.15	.08	.09	.04	.46	.08	.08
MgO	.00	Trace.	.00	.46	.34	.00	Trace.	.00	Trace.	.00	.32
CaO	53.92	53.67	43.77	53.68	54.13	54.16	53.99	53.95	51.18	53.36	53.80
P_2O_5	Trace.	.03	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	.17	Trace.	Trace.
Ignition	44.79	44.77	44.62	44.34	44.36	44.65	44.85	44.93	46.67	45.59	44.10
	99.04	98.76	98.90	98.87	99.12	99.01	99.04	99.00	98.81	99.12	98.30
CO_2 needed	42.37	42.10	42.25	42.69	42.90	42.55	42.41	42.39	39.86	41.93	41.73
Organic matter, etc.	2.42	2.67	2.37	1.65	1.46	2.10	2.44	2.54	6.81	3.66	2.37

MOLLUSKS.

Reduced analyses.

	1	2	3	4	5	6	7	8	9	10
SiO_2	0.26	0.19	0.30	0.32	0.14	0.13	0.11	0.09	0.36	0.1
$(Al,Fe)_2O_3$	.09	.12	.23	.08	.15	.08	.09	.04	.50	.0
$MgCO_3$	.00	Trace.	.00	1.00	.73	.00	Trace.	.00	Trace.	.0
$CaCO_3$	99.65	99.62	99.47	98.60	98.98	99.79	99.80	99.87	98.74	99.8
$Ca_3P_2O_8$	Trace.	.07	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	.40	Trace
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.0

2. SCAPHOPODS AND AMPHINEURANS.

Under this heading we have only two analyses to offer, as follows:

12. *Dentalium solidum* Verrill. Off Georges Bank, east of Cape Cod, Mass.; depth of water, 2,361 met temperature, 4.5° C.

13. *Mopalia muscosa* Gould. Santa Barbara, Cal. A chiton.

Analyses of scaphopods and amphineurans.

Analyses.			Reduced analyses.	
	12	13		12
SiO_2	0.39	0.59	SiO_2	0.40
$(Al,Fe)_2O_3$	.26	.21	$(Al,Fe)_2O_3$	.27
MgO	.09	.25	$MgCO_3$	.20
CaO	53.89	53.42	$CaCO_3$	99.13
SO_3	(?)	.20	$CaSO_4$	(?)
P_2O_5	Trace.	Trace.	$Ca_3P_2O_8$	Trace.
Ignition	44.48	44.74		100.00
	99.11	99.41		
CO_2 needed	42.44	42.13		
Organic matter, etc	2.04	2.61		

3. GASTROPODS.

14. *Purpura lapillus* Linné. Eastport, Maine.

15. *Aporrhais occidentalis* Beck. Off Marthas Vineyard, Mass.; depth of water, 435.5 meters; botton ture, 5.5° C.

16. *Buccinum undatum* Linné. Narragansett Bay, R. I.; depth, 53.3 meters; bottom temperature, 9°

17. *Natica duplicata* Say. Cape Lookout, N. C.

18. *Olivia literata* Lamarck. Sarasota, Fla.

19. *Fasciolaria distans* Lamarck. Sarasota, Fla.

20. *Crepidula onyx* Sowerby. San Pedro, Cal.

21. *Antiplanes perversa* Gabb. Off Bodega Head, Cal.; latitude, 38° 23′ 35″ N.; depth, 112.5 met temperature, 9° C.

22. *Nassa californiana* Conrad. Monterey Bay, Cal.; latitude, 36° 47′ 50″ N.; depth, 67.7 meters; b perature, 11.3° C.

23. *Nassa tegula* Reeve. Musgrove Island, Magdalena Bay, Lower California.

24. *Nassa insculpta* Carpenter. Cortez Bank, Cal.; latitude, 32° 20′ 30″ N.; depth, 165 meters; b perature, 9.5° C.

25. *Turritella gonostoma* Valenciennes. Mulege, Gulf of California.

26. *Volutometra alaskana* Dall. Off Unalaska, Alaska; latitude, 55° N.; depth, 143 meters; bottom te 4.5° C.

27. *Pyrolofusus harpa* Mörch. Unalaska, Alaska.

28. *Plicifusus dirus* Reeve. Sitka Harbor, Alaska.

29. *Tachyrynchus erosa* Couthouy. Avatcha Bay, Kamchatka.

30. *Ranella pulchra* Gray. China Sea, north of Prabas Island; depth, 256 meters; bottom temperature,

31. *Cerithium aluco* Linné. Reef opposite Cebu, Philippine Islands.

32. *Strombus canarium* Linné. Subig Bay, Luzon, Philippine Islands.

33. *Cavolina longirostris* Lesueur. Off Adyagan Island, Philippines; depth, 247 meters.

Analyses of gastropods.

	14	15	16	17	18	19	20	21	22	23
SiO_2	0.14	1.27	0.94	0.00	0.05	0.33	0.15	0.46	0.27	2.07
$(Al,Fe)_2O_3$	.15	.22	.41	.05	.04	.04	.11	.11	.12	.33
MgO	.19	Trace.	.12	Trace.	.00	.06	Trace.	Trace.	.17	.20
CaO	53.34	52.84	52.77	54.83	54.38	53.87	53.63	54.06	53.20	51.30
SO_3	(?)	.08	(?)	(?)	(?)	(?)	.00	(?)	(?)	(?)
P_2O_5	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	.08
Ignition	45.33	44.09	44.49	44.22	44.46	44.49	44.40	44.15	44.84	44.76
	99.15	98.50	98.73	99.10	98.93	98.79	98.29	98.78	98.60	98.74
CO_2 needed	42.12	41.52	41.59	43.08	42.73	42.39	42.14	42.48	41.99	40.37
Organic matter, etc	3.21	2.57	2.90	1.14	1.73	2.10	2.26	1.67	2.85	4.39

	24	25	26	27	28	29	30	31	32	33
SiO_2	0.47	0.25	0.07	0.08	0.16	0.23	2.20	0.00	0.08	0.71
$(Al,Fe)_2O_3$	.47	1.83	.17	.08	.22	.81	.61	.09	.20	.39
MgO	.77	.20	Trace.	Trace.	.11	.44	.23	Trace.	Trace.	.09
CaO	49.32	52.57	53.88	54.23	52.66	49.30	52.63	54.47	54.04	53.73
SO_3	(?)	.11	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)
P_2O_5	.04	Trace.	Trace.	Trace.	Trace.	.36	Trace.	Trace.	Trace.	.38
Ignition	48.00	43.51	44.60	44.42	45.83	47.60	43.31	44.37	44.31	43.82
	99.07	98.47	98.72	98.81	98.98	98.74	98.98	98.93	98.63	99.12
CO_2 needed	39.51	41.46	42.33	42.61	41.50	38.54	41.64	42.80	42.46	41.96
Organic matter, etc	8.49	2.05	2.27	1.81	4.33	9.06	1.67	1.57	1.85	1.86

Reduced analyses.

	14	15	16	17	18	19	20	21	22	23
SiO_2	0.15	1.32	0.98	0.00	0.05	0.34	0.16	0.48	0.28	2.19
$(Al,Fe)_2O_3$	.16	.23	.43	.05	.04	.04	.11	.11	.13	.35
$MgCO_3$	.41	Trace.	.26	Trace.	.00	.14	Trace.	Trace.	.37	.44
$CaCO_3$	99.28	98.30	98.33	99.95	99.91	99.48	99.73	99.41	99.22	96.84
$CaSO_4$	(?)	.15	(?)	(?)	(?)	(?)	.00	(?)	(?)	(?)
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	.18
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	24	25	26	27	28	29	30	31	32	33
SiO_2	0.52	0.26	0.07	0.08	0.17	0.26	2.26	0.00	0.09	0.73
$(Al,Fe)_2O_3$	.52	1.89	.18	.08	.23	.90	.63	.10	.21	.40
$MgCO_3$	1.78	.44	Trace.	Trace.	.24	1.02	.51	Trace.	Trace.	.20
$CaCO_3$	97.08	97.21	99.75	99.84	99.36	97.00	96.60	99.90	99.70	97.82
$CaSO_4$	(?)	.20	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)
$Ca_3P_2O_8$	.10	Trace.	Trace.	Trace.	Trace.	.82	Trace.	Trace.	Trace.	.85
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

MOLLUSKS.

4. CEPHALOPODS.

34. *Nautilus pompilius* Linné. Mindanao, Philippine Islands.
35. *Argonauta argo* Linné; the paper nautilus. High seas, Pacific Ocean.
36. *Sepia* sp.; cuttle-fish bone. Port Tataan, Tawi Tawi group, Philippine Islands.

Analyses of cephalopods.

	34	35	36
SiO_2	0.18	0.08	0.00
$(Al,Fe)_2O_3$	.14	.12	.06
MgO	.07	2.58	.66
CaO	52.44	46.78	47.42
P_2O_5	Trace.	Trace.	Trace.
Ignition	46.65	49.16	51.63
	99.48	98.72	99.77
CO_2 needed	41.28	42.30	38.65
Organic matter, etc	5.37	6.86	2.98

Reduced analyses.

	34	35	36
SiO_2	0.19	0.09	0.00
$(Al,Fe)_2O_3$	.15	.13	.06
$MgCO_3$	.16	6.02	1.62
$CaCO_3$	99.50	93.76	98.32
$Ca_3P_2O_8$	Trace.	Trace.	Trace.
	100.00	100.00	100.00

For comparison a series of four analyses of cephalopod shells by O. I citing in full. They are as follows:

1. *Nautilus pompilius.* 2. *Argonauta argo.* 3. *Spirula peronii.* 4. *Sepia officinalis.*

Analyses of cephalopods by Bütschli.

	1	2	3	4
$CaCO_3$	94.75	85.07	90.43	87.36
$MgCO_3$	.16	5.08	.46	.21
Phosphate	.....	3.06	3.20	2.26
$CaSO_4.2H_2O$	.20	1.75	.48	.78
H_2O	2.62	2.92	2.17	4.89
Organic matter	2.03	2.43	2.32	5.36
Sand	.....	.....	.33	.....
	99.76	100.31	99.39	100.86

Exactly what is meant by "phosphate" is not clear. Assuming it to m phate and reducing the analyses to uniformity with ours, they take the follo

Bütschli's analyses reduced.

	1	2	3	4
$CaCO_3$	99.66	89.93	95.75	96.58
$MgCO_3$	.17	5.37	.48	.23
CaP_2O_8	.....	3.24	3.39	2.50
$CaSO_4$	.17	1.46	.38	.69
	100.00	100.00	100.00	100.00

[1] K. Gesell. Wiss. Göttingen Abh., No. 3, 1908. Bütschli also gives analyses of three other mollusks, *Pinna ja Purpura lapillus*, but they show no unusual features.

ısual proportion of magnesium carbonate in *Argonauta* is confirmed by our analysis, phosphate in three of Bütschli's analyses is unlike anything in our series. Possibly sulphate is really present in the hydrated form, that is, as gypsum, but that is However, it is not necessary to make that assumption, and to do so would com- omparison of analyses.

ıe evidence now at hand and from many older data it is clear that molluscan shells ɔst entirely of calcium carbonate with quite insignificant impurities. The only ɔption is *Argonauta*, which contains 6 per cent of magnesium carbonate, but the .us has no importance as a contributor to the marine sediments. The mollusks e of immense importance, a fact to which their fossil remains abundantly testify. ion they resemble the corals and millepores, so much so that an analysis from one readily pass for an analysis from the other.[1]

CRUSTACEANS.

ɔrustaceans analyzed in the course of this investigation fall into two distinct groups. arnacles, which have shells composed mainly of calcium carbonate with very little ter. Second, a group of the more familiar crustaceans, such as crabs, shrimps, and hese have shells containing notable amounts of calcium phosphate and much ter. The analyses of the first group cover the following species:

ıatifera Linné. Florida.
ıserifera Linné. Woods Hole, Mass.
polymerus Sowerby. Pacific Grove, Cal.; latitude, 36° 36′ N.; longitude, 121° 55′ W.
hameri Ascanius. Georges Bank, east of Cape Cod, Mass.
amphitrite niveus Darwin. Cape May, N. J.
eburneus Gould. Smiths Creek, Potomac River, Md.
um regium Wyville Thomson and Hoek. *Albatross* station 3342; off Queen Charlotte Islands; latitude, longitude, 132° 38′ W.; depth of water, 2,906 meters; bottom temperature, 18° C.

alyses are as follows:

Analyses of barnacles.

	1	2	3	4	5	6	7
	0.04	0.04	0.08	0.03	1.99	0.39	0.73
	.19	.56	.30	.14	.68	.22	
	1.14	.86	.94	.35	.73	.76	1.03
	52.33	52.53	50.83	53.57	50.09	53.23	52.65
	Trace.	.34	Trace.	.00	Trace.	Trace.	Trace.
	44.50	43.90	46.18	44.39	44.84	44.28	44.79
	98.20	98.23	98.33	98.48	98.33	98.88	99.20
	42.37	41.82	40.97	42.47	40.16	42.67	42.48
	2.13	2.08	5.21	1.92	4.68	1.61	2.31

Reduced analyses.

	1	2	3	4	5	6	7
	0.04	0.04	0.09	0.03	2.12	0.40	0.75
	.20	.58	.33	.15	.72	.22	
	2.49	1.87	2.11	.75	1.63	1.65	2.23
	97.27	96.74	97.47	99.07	95.53	97.73	97.02
	Trace.	.77	Trace.	.00	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

ıal data see L. Schmelck, Norske Nordhavs Exped., No. 28, p. 129, 1901. Fourteen analyses of molluscan shells are given, of *num*, *Astarte*, *Neptunea*, and *Pecten*, all from the North Sea. The highest percentage of magnesium carbonate found was 0.78, For ten complete analyses of oyster shells see Chatin, A., and Muntz, A., Compt. Rend., vol. 120, p. 531, 1895. For eleven analyses an inaugural dissertation by A. Döring, Göttingen, 1872. Several determinations of magnesium carbonate, maximum 1 per r G. Forchhammer in Neues Jahrb., 1852, p. 854.

Sulphates and soluble salts were not determined. Except for the slightly higher n these analyses closely resemble those of mollusks.

One analysis of a barnacle, *Balanus tintinnabulus*, by Bütschli,[1] is essentially simila His figures are—

$CaCO_3$	9
$MgCO_3$	
$Ca_3P_2O_8$	
$CaSO_4.2H_2O$	
	9

In all the analyses calcium carbonate is the main constituent, and there are on impurities. We have found no other analysis of a barnacle recorded.

In the second group of crustaceans the following species were analyzed:

1. *Tryphosa pinguis* Boeck; sand flea. Woods Hole, Mass.
2. *Pagurus rathbuni* Benedict; hermit crab. Bering Sea; *Albatross* station 3531; latitude, 50° 55′ N.; 174° 17′ W.; depth of water, 105 meters; bottom temperature, 1.7° C.
3. *Callinectes sapidus* M. J. Rathbun; blue crab. Ranges from Cape Cod to Florida.
4. *Homarus americanus* Milne Edwards; common lobster. Vineyard Sound, Mass.
5. *Pandalus platyceros* Brandt; shrimp. Off Monterey Bay, Cal.; *Albatross* station 3129; latitude, 36° 3 longitude, 122° 01′ W.; depth, 49.4 meters; bottom temperature, 6.5° C.
6. *Lithodes maia* Linné; spider crab. North Atlantic coast, precise locality of specimen unknown.
7. *Libinia emarginata* Leach; spider crab. Vineyard Sound, Mass.
8. *Munida iris* Milne Edwards; long-armed munida. Off Chesapeake Bay; *Albatross* station 2420; latitu 20″ N.; longitude, 74° 31′ 40″ W.; depth, 190.3 meters; bottom temperature, 8.7° C.
9. *Crago dalli* Rathbun; a shrimp. Off Cape Stroganoff, Alaska; *Albatross* station 3294; latitude, 57° 1 longitude, 159° 03′ 30″ W.; depth, 54.9 meters; bottom temperature, 5° C.
10. *Panulirus argus* Latreille; spiny lobster. West Indies.
11. *Chloridella empusa* Say; mantis shrimp. Ranges from Cape Cod to Florida.
12. *Penæus brasiliensis* Latreille; edible shrimp. Ranges from New York to Brazil.

Analyses of crustaceans.

	1	2	3	4	5	6	7	8	9	10
SiO_2	0.62	0.16	0.04	0.00	0.32	0.00	2.61	0.32	0.62	0.
$(Al,Fe)_2O_3$	.37	.15	.04	.21	.26	.15	.78	.16	.20	.
MgO	1.27	1.55	2.06	2.35	1.44	1.90	2.81	2.58	1.01	3.
CaO	28.63	29.11	33.42	31.35	18.56	24.15	32.79	31.28	9.95	25.
P_2O_5	4.56	3.25	4.26	3.04	4.60	3.51	2.73	1.87	2.65	2.
SO_3	.23	.75	.23	.45	.54	.63	.49	.47	.47	.
Ignition	64.73	64.50	58.89	61.82	73.81	69.00	57.07	62.29	83.70	66.
	100.41	99.47	98.94	99.22	99.53	99.34	99.28	98.97	98.60	97.
CO_2 needed	19.53	21.14	24.43	24.08	11.58	17.46	26.05	25.41	6.20	21.
Organic matter, etc.	45.20	43.36	34.46	37.74	62.23	51.54	31.02	36.88	77.50	45.

In No. 12, the common edible shrimp of the Washington (D. C.) markets, the shell w that the available material was too small for complete analysis. Only P_2O_5, 3.07 per determined.

Reduced analyses.

	1	2	3	4	5	6	7	8	9	10
SiO_2	1.12	0.28	0.06	0.00	0.87	0.00	3.82	0.52	2.94	0.
$(Al,Fe)_2O_3$	.67	.27	.06	.34	.70	.31	1.14	.27	.95	.
$MgCO_3$	4.84	5.80	6.69	8.02	8.09	8.35	8.65	8.71	10.05	12.
$CaCO_3$	74.64	78.03	78.14	79.50	60.94	73.07	76.44	82.64	54.83	76.
$Ca_3P_2O_8$	18.02	13.55	14.45	10.91	26.94	16.03	8.73	6.57	27.44	8.
$CaSO_4$	.71	2.07	.60	1.23	2.46	2.24	1.22	1.29	3.79	1.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.

[1] K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.

› crustaceans of this second group are very different in composition from the barnacles. e distinctly phosphatic, a fact which was already known, and they are also notably an, a peculiarity which, with a single exception, to be noted later, seems to have escaped ıttention hitherto. The proportion of magnesium carbonate appears to be somewhat nt on temperature, as was shown in our analyses of echinoderms and alcyonarians; evidence for such a variation is not conclusive. Analysis 2, of a crab from Bering Sea, magnesia; analysis 10, of a West Indian specimen, is high. Analyses 5, 6, 7, and 8 are liate in their magnesian content, and so far as can be determined from the evidence before represent specimens from waters of intermediate and similar temperatures. Unfortuıe records for some specimens are defective as to precise localities and temperatures. Fure, the large amounts of organic matter and water render the reduced analyses to some ınsatisfactory. This is especially true of analysis No. 9, in which the inorganic portion ɔd to only 21 per cent. In reducing such an analysis the unavoidable analytical errors tiplied, and the percentages of magnesium carbonate, calcium carbonate, and calcium te may be uncertain by as much as 1 per cent each. In no case is the order of de seriously changed, but the accuracy of the figures is not what we should wish it to be. iation in the percentages of magnesium carbonate is, however, suggestive, in spite of ɔr apparent irregularities.

› older analyses of the shells of crustaceans are more or less unsatisfactory, but they all to the phosphatic character of these organisms. C. Schmidt,[1] for example, gives three ı, as follows:

tacus fluviatilis; fresh-water crawfish. 53.27 per cent inorganic.
bster; probably either *Homarus vulgaris* or *Palinurus*. 77.06 per cent inorganic.
uilla mantis; a shrimp. 37.17 per cent inorganic.

Schmidt's analyses of crustaceans.

	1	2	3
$Ca_3P_2O_8$.....	13.17	12.06	47.52
$CaCO_3$.....	86.83	87.94	52.08
	100.00	100.00	100.00

› figures given here are for the inorganic matter alone. Schmidt mentions magnesium te as present but gives no determinations of it.

ɔ analyses of crustacean shells by E. Fremy[2] are also worth citing:

angouste"; *Palinurus vulgaris.*
crevisse"; probably the crawfish, *Astacus fluviatilis.*

Fremy's analyses of crustaceans.

	1	2
$Ca_3P_2O_8$.....	6.7	6.7
$CaCO_3$.....	49.0	56.8
Organic matter....	44.3	36.5
	100.0	100.0

ɛe, again, the determination of magnesia has been neglected. If we reject the organic the percentages of calcium phosphate in the inorganic part of the shells become 12.03 55, respectively.

nnalen Chemie Pharm., vol. 54, p. 303, 1845.
nnales chimie et phys., 3d ser., vol. 43, p. 94, 1855. Fremy also gives many analyses of vertebrate bones, both recent and fossil.

Astacus fluviatilis seems to have received more attention from chemists than any other crustacean. H. Weiske [1] found in fresh shells 4.97 to 5.31 per cent of calcium phosphate and in old shells, partly cast off, 9.16 to 9.21 per cent. In "Krebsteine," the concretions found in the shells, the percentages ran from 10.73 to 11.28 per cent. The total inorganic matter varied between 61 and 67 per cent.

Astacus has also been studied by Agnes Kelly,[2] who also analyzed a myriapod, *Julus* (*Iulus*). Her figures are as follows:

Analyses by Agnes Kelly.

	Astacus.	Julus.
CaO	30.44	36.29
CO_2	21.23	21.60
P_2O_5	2.79	3.37
	54.52	56.26

In an analysis of *Astacus fluviatilis* by O. Bütschli [3] magnesia was actually determined. We append his analysis, together with our own reduction of it:

Bütschli's analysis of Astacus.

Actual analysis.		Reduced analysis.	
$CaCO_3$	47.51	$CaCO_3$	83.40
$MgCO_3$	1.38	$MgCO_3$	2.42
Phosphate	6.77	$Ca_3P_2O_8$?	11.88
$CaSO_4.2\,H_2O$	1.66	$CaSO_4$	2.30
H_2O	1.34		100.00
Organic matter	40.60		
	99.26		

In this analysis the low percentage of magnesia is very significant. *Astacus* is a fresh-water crustacean, whereas the analyses in our series are all of marine forms. In fresh water—the average river water—calcium is 6 times as abundant as magnesium, but in ocean water magnesium is 3½ times as abundant as calcium. This difference in the environment may possibly explain the difference between the fluviatile and the marine shells, 2.42 per cent of $MgCO_3$ in one and 4.84 per cent in the lowest of our determinations.

One more determination of phosphoric oxide in a crustacean remains to be noted. In the shell of a lobster, *Homarus vulgaris*, W. H. Hudleston [4] found 3.26 per cent of P_2O_5. This is equivalent to 7.12 per cent of $Ca_3P_2O_8$, or, if the organic matter was about the same in amount as in our analysis of the American lobster, 11.44 per cent in the inorganic portion alone. This is not far from the figure given in our reduced analysis No. 4, namely, 10.91 per cent.

Although the crustaceans are not of great importance as contributors to the marine sediments, they are more important than appears at a casual glance. A crab or lobster sheds its shell annually and grows a new one, so that an old individual has contributed many times. A single shell might count for little, but when multiplied by a dozen or more the contributions become significant. How significant they may be is for zoologists to determine.

[1] Landwirthschaftliche Versuchsstationen, vol. 20, p. 45, 1877.
[2] Jenaisches Zeitschr., vol. 35, p. 429, 1901.
[3] K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.
[4] Geol. Soc. Quart. Jour., vol. 31, p. 376, 1875.

CALCAREOUS ALGÆ.

The calcareous algæ are so important as reef builders that, although they are not marine invertebrates in the ordinary acceptance of the term, it seemed eminently proper to include them in this investigation. In many places they far outrank the corals in importance, and of late years much attention has been paid to them. To Dr. Marshall A. Howe, of the New York Botanical Garden, we are indebted for a fine series of algæ, and to him we express our thanks.

For the purposes of this research the calcareous algæ fall into two groups. One of these, of which *Lithothamnium* is the most familiar example, is highly magnesian; the other, represented by *Halimeda*, is almost free from magnesia. These groups are best considered separately, and under the first one we have the following species:

1. *Lithothamnium glaciale* Kjellman. Topsail, Conception Bay, Newfoundland; latitude, 48° N.; longitude, 53° W.
2. *Lithothamnium erubescens* Foslie. Haingsisi, near Timor, East Indian Archipelago.
3. *Archæolithothamnium episporum* Howe. Point Toro, near Colon, Isthmus of Panama.
4. *Lithophyllum craspedium* Foslie. Palmyra Island, in the Pacific Ocean, west of south from Hawaii; latitude, 5° 49′ N.
5. *Lithophyllum pallescens* Foslie. Bay of La Paz, Gulf of California; latitude, 24° 16′ N.
6. *Lithophyllum dædalium* Foslie and Howe. Salinas Bay, near Guanica, Porto Rico; latitude, about 18° N.
7. *Lithophyllum antillarum* Foslie and Howe. Culebra Island, Porto Rico; latitude, about 18° 20′ N.
8. *Lithophyllum oneodes* Heydrich. Coetivy Island, in the Indian Ocean, northeast of Madagascar; latitude, 7° 6′ S.; longitude, 56° 30′ E.
9. *Lithophyllum intermedium* Foslie. Fort Kingston, near Clarence, Jamaica.
10. *Lithophyllum pachydermum* Foslie. Dollar Harbor, South Cat Cay, Bahamas; latitude, about 25° N.
11. *Lithophyllum tamiense* Heydrich. New Guinea.
12. *Amphiroa fragilissima* Lamouroux. Lemon Bay, near Guanica, P. R.
13. *Phymatolithon compactum* Foslie. Torbay, Newfoundland.
14. *Goniolithon acropetum* Foslie and Howe. Culebra Island, P. R.
15. *Goniolithon strictum* Foslie. Bemini Harbor, Bahamas.
16. *Goniolithon strictum.* Soldiers Key, Fla.

The actual analyses are as follows:

Analyses of algæ.

	1	2	3	4	5	6	7	8
SiO_2	0.41	0.19	1.47	0.03	1.01	0.18	0.04	0.09
$(Al,Fe)_2O_3$	.23	.12	.89	.09	.22	.08	.10	.12
MgO	4.78	7.52	5.93	8.64	6.42	8.14	7.24	8.07
CaO	45.41	42.96	44.80	41.56	40.39	40.48	43.34	42.57
P_2O_5	Trace.	Trace.	Trace.	.03	.11	Trace.	Trace.	.08
SO_3	.14	.61	.53	.15	.71	.44	.57	.27
Ignition	48.00	47.89	45.69	48.37	49.94	49.99	48.11	47.96
	98.97	99.29	99.31	98.87	98.80	99.31	99.40	99.16
CO_2 needed	40.86	41.69	41.43	42.04	38.31	40.51	41.70	42.11
Organic matter, etc	7.14	6.20	4.26	6.33	11.63	9.48	6.41	5.85

	9	10	11	12	13	14	15	16
SiO_2	0.27	0.04	0.12	2.82	0.10	0.06	0.02	0.05
$(Al,Fe)_2O_3$	.21	.08	.16	1.31	.23	.04	.01	
MgO	7.25	6.47	8.81	6.71	4.02	8.27	10.39	10.93
CaO	42.55	42.60	41.07	34.82	38.19	40.60	38.54	38.03
P_2O_5	Trace.	.00	Trace.	Trace.	.10	.18	Trace.	Trace.
SO_3	.02	.59	.69	.56	.52	.62	.60	.61
Ignition	48.63	49.55	48.77	48.78	55.42	49.56	49.91	49.91
	98.93	99.33	99.62	95.00	98.58	99.33	99.47	99.53
CO_2 needed	41.89	40.24	41.58	34.43	35.05	40.50	41.38	41.56
Organic matter, etc	6.74	9.31	7.19	14.35	20.37	9.06	8.53	8.35

The low summation of No. 12, a very fragile form, is due to inclosed salts, mainly a chlorides and sulphates. These were determined as 5.40 per cent, which brings the sum up to 100.40.

Reducing the analyses, as usual, to standard form, we have the following table:

Reduced analyses.

	1	2	3	4	5	6	7
SiO_2	0.45	0.20	1.55	0.03	1.16	0.20	0.04
$(Al,Fe)_2O_3$	.25	.13	.94	.10	.25	.09	.11
$MgCO_3$	10.93	16.96	13.09	19.60	15.46	19.03	16.35
$CaCO_3$	88.11	81.59	83.47	79.92	81.48	79.85	82.46
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	.08	.26	Trace.	Trace.
$CaSO_4$	.26	1.12	.95	.27	1.39	.83	1.04
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	9	10	11	12	13	14	15
SiO_2	0.30	0.04	0.13	3.50	0.13	0.07	0.02
$(Al,Fe)_2O_3$	.23	.09	.17	1.62	.30	.05	.01
$MgCO_3$	16.59	15.08	20.02	17.47	10.93	19.24	24.00
$CaCO_3$	82.85	83.68	78.43	76.23	87.21	79.05	74.85
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	.29	.43	Trace.
$CaSO_4$	.03	1.11	1.25	1.18	1.14	1.16	1.12
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

In No. 12, *Amphiroa*, the high silica and sesquioxides are evidently impurities.] are rejected, the percentage of magnesium carbonate rises to 18.41.

Of *Halimeda*, four species were analyzed, as follows:

17. *Halimeda opuntia* Lamouroux. Key West, Fla.
18. *Halimeda simulans* Howe. East of Guanica Harbor, Porto Rico.
19. *Halimeda tridens* Lamouroux. Cayo Maria Langa, Bay of Guayanilla, Porto Rico.
20. *Halimeda monile* Lamouroux. Same locality as No. 19.

Analyses of Halimeda.

	17	18	19
SiO_2	0.37	0.44	0.88
$(Al,Fe)_2O_3$	.20	.18	.58
MgO	.01	.19	.44
CaO	50.32	50.20	45.32
P_2O_5	Trace.	Trace.	Trace.
SO_3	.07	.23	.49
Ignition	48.20	48.38	51.94
	99.17	99.62	99.65
CO_2 needed	39.47	39.53	35.83
Organic matter, etc	8.73	8.85	16.11

Reduced analyses.

	17	18	19
SiO_2	0.41	0.48	1.04
$(Al,Fe)_2O_3$	.22	.20	.68
$MgCO_3$	.02	.44	1.09
$CaCO_3$	99.21	98.45	96.21
$Ca_3P_2O_8$	Trace.	Trace.	Trace.
$CaSO_4$	.14	.43	.98
	100.00	100.00	100.00

After allowance is made for obvious impurities the essential identity of these four analyses becomes clear. The inorganic portion of *Halimeda* consists of calcium carbonate and an insignificant amount of magnesia. In the first group of algæ, Nos. 1 to 16, magnesium carbonate is conspicuous, more so than in any other class of organisms so far analyzed. In *Goniolithon strictum* especially it ranges from 24 to over 25 per cent, or more than half way to dolomite These algæ are probably the largest contributors of magnesia to the marine limestones.

It is also noteworthy that the two algæ of the first group, Nos. 1 and 13, are from the cold waters of Newfoundland, and that the others are from tropical or subtropical regions. Several, if not all of them, are shoal-water organisms and were collected on reefs, or rocks, or on sands near low-tide levels. It is desirable that Arctic species should be carefully studied—at least more carefully than hitherto. The older published data leave much to be desired, especially as to definiteness of species and localities.

Of the earlier analyses of calcareous algæ those by A. Damour[1] are the most complete and most nearly comparable with ours. Five species were analyzed, as follows:

1. *Lithophyllum* sp. Mediterranean Sea.
2. *Melobesia* sp. Coast of Algeria.
3. *Amphiroa tribulus*. Antilles.
4. *Halimeda opuntia*. Red Sea.
5. *Galaxaura fragilis*. Antilles.

Damour's "*Millepora cevricornis*," of which he gives an analysis, is not included here on account of its doubtful character. (See p. 18.)

Damour's analyses of algæ.

	1	2	3	4	5
$CaCO_3$	77.36	72.78	70.83	86.17	72.56
$MgCO_3$	11.32	12.32	16.99	.56	.86
Na_2O	.55	1.75	.89	1.13	.73
K_2O	.27	.65	.39	.54	1.02
Fe_2O_3	.08	.20	.....	.....	.....
SO_3	.95	1.25	.93	(?)	(?)
P_2O_5	.32	.38	.27	(?)	(?)
Cl	.60	.34	.53	.84	1.17
$CaSO_4$	.....	.....	.20	.55	1.80
Organic matter	4.70	3.95	6.40	8.30	17.50
H_2O	1.46	1.40	1.38	.90	.95
SiO_2	.....	.....	.....	.....	2.20
Sand	1.36	4.28	.....	.....	.....
	98.97	99.30	98.81	98.99	98.79

In these analyses Na_2O, K_2O, Cl, and SO_3 evidently represent sea salts. Rejecting them as impurities, together with the organic matter, water, and sand, and recalculating to 100 per cent, we have the following reduced analyses, which are similar to ours:

Damour's analyses reduced.

	1	2	3	4	5
SiO_2	.....	.....	.....	.....	2.84
Fe_2O_3	0.09	0.23	.....	.....	.....
$MgCO_3$	12.76	14.44	19.29	0.64	1.11
$CaCO_3$	86.36	84.36	79.81	98.73	93.73
$Ca_3P_2O_8$	.79	.97	.67	(?)	(?)
$CaSO_4$	.....	.....	.23	.63	2.32
	100.00	100.00	100.00	100.00	100.00

[1] Compt. Rend., vol. 32, p. 253, 1851.

Three of these algæ are highly magnesian; *Halimeda* and *Galaxaura* are not.

Two analyses of algæ by A. Schwager were published by J. Walther[1] in 1885. also one by C. W. Gümbel,[2] and these three may be combined in one table, as follows:

1. *Lithothamnium* sp. Bay of Naples; Schwager, analyst.
2. *Lithothamnium ramulosum.* Bay of Naples; Schwager, analyst.
3. *Lithothamnium nodosum.* Locality not stated; Gümbel, analyst.

Actual analyses of algæ.

	1	2	
SiO_2	1.59	1.91	...
Al_2O_3	3.36	3.61	}
Fe_2O_3	.28	.41	}
MnO	Trace.	Trace.	}
MgO	1.90	3.06	
CaO	48.09	45.88	
CO_2	39.87	39.41	
P_2O_5	.....	.....	
Organic matter+H_2O	5.06	5.57	...
Insoluble	.....	.....	
H_2O and loss	.....	.....	
	100.15	99.85	

Reducing these to uniformity with our analyses we have the following table:

Reduced analyses.

	1	2	
SiO_2	1.68	2.03	...
$(Al,Fe)_2O_3$	3.83	4.26	
$MgCO_3$	4.19	6.81	
$CaCO_3$	90.30	86.90	
$Ca_3P_2O_8$	.....	.....	
	100.00	100.00	

In these analyses, all of *Lithothamnium*, the percentage of magnesium carbonate is ably low. Why this should be so is not clear, but it may be due to differences in th the plants; that is, young specimens may have secreted less magnesia proportionally than older, more mature examples. This suggestion might well be tested by special of properly selected material. Until that has been done the suggestion can carry little

Eleven partial analyses of *Lithothamnium*, made by A. G. Högbom,[3] assisted by R. lius, N. Sahlbom, and J. Guinchard, are curiously irregular. The percentages of ma carbonate vary enormously, and with no apparent or even probable relation to temp The data given are as follows:

	$CaCO_3$.
Lithothamnium sp. Java Sea	72.03
Lithothamnium sp. Galapagos Islands	83.60
Lithothamnium sp. Spitzbergen	84.83
Lithothamnium polymorphun. Kattegat	74.22
Lithothamnium sp. Honolulu	84.01
Lithothamnium ramulosum. Naples	63.00
Lithothamnium soriferum. Arctic Ocean	80.90
Lithothamnium sp. Bering Islands	74.24
Lithothamnium racemus. Naples	77.39
Lithothamnium sp. Bermuda	82.44
Lithothamnium glaciale. Arctic Ocean	83.10

[1] Deutsch. geol. Gesell. Zeitschr., p. 338, 1885.
[2] K. bayer. Akad. Wiss. Abh., Math.-phys. Classe, vol. 2, p. 26.
[3] Neues Jahrb., 1894, Band 1, p. 262.

In this series the percentages of magnesium carbonate are much lower than those found by us, and there is uncertainty in six examples as to the exact species. Högbom, however, points out the importance of these algæ in respect to the formation of dolomite, which was the real subject of his investigation. In *Halimeda* sp., from Labuan, only a trace of magnesia was found.

In *Lithothamnium racemus*, from the Bahamas, H. W. Nichols[1] found 5.35 per cent of magnesium carbonate, but without rejection of organic matter, etc., undetermined. This percentage is remarkably low. A similar low figure for magnesium carbonate—5.85 per cent—was found by E. W. Skeats[2] in *Lithothamnium phillipi* var. *funafutiensis* Foslie. The specimen was taken on the atoll of Funafuti.

In a very fresh *Halimeda opuntia* Skeats found 0.60 per cent of $MgCO_3$ and 86.50 of $CaCO_3$, but in a mass of fronds dredged up from a depth between 50 and 60 fathoms the percentages were 4.0 $MgCO_3$ to 93.59 $CaCO_3$. The increase in magnesia may have been due to concentration by leaching. These data are given by J. W. Judd,[3] who also cites an analysis of dead *Halimeda* fronds made for him by C. G. Cullis, who found in them 1.39 per cent of $MgCO_3$ and 98.32 of $CaCO_3$. Judd also quotes an analysis of *Halimeda*, cited by Payen in his Flora, which contained 5.50 per cent of $MgCO_3$ and 90.16 of $CaCO_3$. The character of the specimen represented by the last analysis, whether fresh or old, is uncertain. The best analyses agree in assigning little magnesium to *Halimeda*.

In an important memoir on *Melobesia* Madame P. Lemoine[4] gives several analyses of calcareous algæ. The analyses, made for her by M. Charf, are not very complete, but they are, nevertheless, of distinct value. The data are as follows:

1. *Lithothamnium calcareum*. St.-Vaast-la-Hougue, Manche, France.
2. *Lithothamnium calcareum*. Isle Glenan, Finistere, France.
3. *Lithothamnium fornicatum*. Norway.
4. *Lithophyllum incrustans*. Gatteville, Manche, France.
5. *Lithophyllum incrustans*. Mazagan, Morocco.
6. *Lithophyllum tortuosum*. Genoa.
7. *Lithophyllum craspedium*. Tahiti.

To the analyses as reproduced in the following table we venture to add a line for reduced or corrected magnesium carbonate, computed on the basis of 100 per cent for the two carbonates alone.

Lemoine's analyses of algæ.

	1	2	3	4	5	6	7
Soluble in H_2O	2.3	3.0	1.2	1.7	3.8	5.7	3.2
Insoluble in HCl	.0	.0	.0	.0	.0	6.2	.0
$CaCO_3$	80.9	75.2	81.6	84.4	77.7	73.4	75.4
$MgCO_3$	11.8	10.7	9.3	10.8	9.8	9.3	15.9
Organic matter	5.0	11.1	7.9	3.1	8.7	5.4	5.5
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
$MgCO_3$ corrected	12.7	12.5	10.2	11.3	11.2	11.2	17.4

In this series the highest magnesia is in the alga from Tahiti and the lowest in that from Norway. This tendency toward increased magnesia in algæ from warm regions, as compared with those from cold waters, was noticed by Madame Lemoine, but only incidentally. The subject was not given any detailed consideration by her.

Madame Lemoine also cites the older analyses of algæ, including three by J. Chalon, as follows:

1. *Lithothamnium calcareum*. Roscoff, Finistere, France.
2. *Lithophyllum incrustans*. Banyuls, France, on the Mediterranean.
3. *Lithophyllum tortuosum*. Naples.

[1] Field Columbian Mus. Pub. 111, p. 31, 1906.
[2] The atoll of Funafuti, pp. 376, 377, London, The Royal Society, 1904.
[3] Idem.
[4] Inst. océanographique Monaco Annales, vol. 2, fasc. 2, 1911.

Chalon's analyses of algæ.

	1	2	3
$CaCO_3$	82.41	76.06	82.20
$MgCO_3$	11.80	14.38	11.57
Organic matter	4.30	7.38	5.26
Water	.86	1.72	.80
	99.37	99.54	99.83
$MgCO_3$ corrected	12.52	15.90	12.35

These recent analyses, from the memoir of Madame Lemoine, agree well with ours and, notwithstanding Högbom's divergent data, strengthen the suggestion that the proportion of magnesia in the algæ is influenced by temperature.

The material studied by us was carefully chosen by Dr. Howe, with direct reference to the purpose of our investigation. Every species was thoroughly identified, its locality was definitely stated, and the specimens were remarkably clean and free from misleading impurities. The results obtained by us are therefore as nearly trustworthy as it is practicable for us to make them. The significance of the algæ in reference to dolomite was already well established by previous workers, but our new data strengthen the conclusions which our predecessors had drawn.[1]

ADDENDA.

Since the foregoing pages were written three more calcareous algæ have been submitted for analysis by T. Wayland Vaughan. The species, with analyses by A. A. Chambers, are as follows:

1. *Goniolithon fratescens* Foslie. Cocos-Keeling Islands, in the Indian Ocean, latitude 12.5° S.; longitude 96.53° E.
2. *Goniolithon orthoblastum* (Heydrich) Howe. Murray Island, Torres Straits, Australia.
3. *Lithophyllum kaiseri* Heydrich. Cocos-Keeling Islands.

Analyses of algæ.

	1	3	3
SiO_2, Al_2O_3, Fe_2O_3	0.07	0.11	0.28
MgO	6.29	5.71	7.09
CaO	46.16	42.39	45.92
P_2O_5	Trace.	Trace.	Trace.
SO_3	.00	.00	.00
Ignition	46.70	50.97	45.72
	99.22	99.18	99.01
CO_2 needed	43.19	39.59	43.88
Organic matter, etc	3.51	11.38	1.84

Reduced analyses.

	1	2	3
SiO_2, Al_2O_3, Fe_2O_3	0.07	0.12	0.29
$MgCO_3$	13.80	13.66	15.33
$CaCO_3$	86.13	86.22	84.38
$Ca_3P_2O_8$	Trace.	Trace.	Trace.
$CaSO_4$	.00	.00	.00
	100.00	100.00	100.00

[1] On the importance of algæ as reef builders see an interesting paper by Dr. Howe in Science, new ser., vol. 35, p. 837, 1912. He cites much other literature.

These algæ are much lower in magnesia than our specimens from similarly warm regions. The two species of *Goniolithon* contain little more than half as much magnesium carbonate as the species from Florida and the West Indies. For this difference we have no explanation to offer.

GENERAL DISCUSSION.

In the foregoing pages we have reported 250 new analyses of marine invertebrates and have cited many other analyses made elsewhere. These data shed much light upon the chemistry of the marine sediments, and they also suggest various problems, some of them biological, which are yet to be solved. The limitations of our research have been pointed out in the introduction to this memoir, and are taken for granted in the following general discussion of the results that we have obtained. First in order we may consider the distribution of the essential constituents of the invertebrate skeletons, taking each one separately.

Silica.—The skeletons of radiolarians and diatoms and the spicules of siliceous sponges consist almost entirely of opaline silica. The radiolarian and diatom oozes of the *Challenger* expedition show the importance of these organisms. In our own work we have studied only the sponges, and our results show nothing new. Our analysis of *Euplectella*, however, is probably more complete than any previous analysis of a siliceous sponge. We have found recorded in the literature only partial analyses of sponge spicules.

In nearly all our analyses, in every group of organisms, silica appears, generally in small but exceptionally in rather large proportions. Some of this may be essential, but in most cases it is an impurity. In fact, sand grains were distinctly visible in some of the specimens analyzed but were not readily removable.

Alumina and iron oxide.—In most of our analyses alumina and iron oxide were usually determined but they are to be regarded generally as impurities due to adherent silt or mud. Iron is doubtless a normal constituent in small amounts.

Lime.—The most important base in nearly all marine shells or skeletons, whether vertebrate or invertebrate, is lime. Only the siliceous organisms are free from it. Molluscan shells, the stony corals, the hard parts of millepores, some brachiopods, and the barnacles are composed almost entirely of calcium carbonate and contain only minor impurities. In the other series of marine invertebrates, with few exceptions, it is the dominant inorganic constituent. Calcium phosphate and sulphate were also determined in most of our analyses, but they will be considered in other paragraphs.

Magnesia.—One of the most interesting results of our investigation is the discovery that magnesium carbonate is much more widely distributed as an essential constituent of marine invertebrates than it has hitherto been supposed to be. In the Foraminifera, alcyonarians, echinoderms, crustaceans, and coralline algæ it is especially important, and some other organisms contain it in notable proportions. Its peculiar relations to temperature have been noted in several sections of this work and will be discussed more fully later.

Our determinations of magnesia, however, are subject to at least one small correction. Many of the specimens analyzed contained inclosed or adherent sea salts and in a few of them it could not be estimated. They rarely amounted to more than 2 per cent but in one analysis 5 per cent was found. Sea salts contain magnesium, and its equivalent in magnesium carbonate must therefore be deducted from the percentages of magnesium carbonate given in our reduced analyses. The maximum correction to be thus applied is about 0.4 per cent but 0.1 per cent would be the more common amount. In our work such a correction is negligible, for the proportion of magnesium carbonate in our important magnesian series ranges from 5 to 25 per cent. The small quantities of magnesia found in most mollusks and corals, however, may be due in part, if not entirely, to saline impurities.

Phosphorus.—In nearly all our analyses phosphoric oxide appears, but generally in trifling quantities. It is abundant, however, in the series of phosphatic brachiopods, the crustaceans, and the alcyonarians. Some worm tubes also are notably phosphatic. In reducing the analyses to standard form we have assumed that the phosphoric oxide is best represented

in combination as tricalcium phosphate, although the assumption is not absolutely proved. It is a pure convention, adopted for the sake of uniformity and to simplify the comparison of analyses. It is of course possible that magnesium phosphates may exist in some of the organisms and that a part of the phosphorus may be contained in their organic matter. Magnesium phosphates, however, are very rare as minerals, whereas calcium phosphate is extremely common. The organic matter decomposes after the death of the animals and its phosphorus would doubtless appear in the sediments as a phosphate. In any case the dead organisms are likely to be buried among calcareous sediments, where calcium phosphate should be formed. Even the phosphatic worm tubes, in which the calcium is insufficient to form a tribasic salt, would probably follow this rule. Lime from the sediments would supply the deficiency.

Sulphur.—In many of our analyses sulphur was determined as sulphur trioxide and recalculated into the form of calcium sulphate. Part of the sulphur may really exist in organic combination, especially in the phosphatic brachiopods, and another part may be derived from sea salts, but this part is extraneous and should not be considered as contributory to the sediments. A correction for them would be like that which we have regarded as applicable to the magnesia and of the same order of magnitude. In the marine sediments generally calcium sulphate is of minor importance.

Other constituents.—Among the inorganic constituents of invertebrates there are other elements than those which we have determined. The most important one of these is fluorine, which is probably present in small amount in all living organisms. P. Carles,[1] for example, has detected fluorine in the shells of mollusks—as much as 0.012 per cent in oyster shells. In combination with calcium phosphate fluorine may form a compound analogous to or identical with apatite. Its presence in vertebrate bones is well known. Boron also is widely distributed in the animal kingdom. G. Bertrand and H. Agulhon [2] detected it in crustaceans, mollusks, and echinoderms, as well as in vertebrate animals. The presence of manganese has been reported in sponges and mollusks [3] and the element is probably of common occurrence in other organisms. Copper has long been recognized in oysters, and was found by L. B. Mendel and H. C. Bradley,[4] together with zinc, iron, magnesium, and phosphorus, in the liver of another mollusk, *Sycotypus*. M. Henze [5] also detected copper in the liver of cephalopods. In two corals G. Forchhammer [6] found traces of copper, silver, and lead. The blood of ascidians, according to Henze,[7] contains vanadium. In short, a systematic search for minor metallic constituents in marine invertebrates would probably show that they contain many other elements. This subject, however, lies outside the scope of our investigation, and these few citations are enough for present purposes.

For the intensive study of coral reefs the analyses furnished by us together with those cited from others are of great significance. The limestone immediately below the zone of living forms owes its composition to all the organisms that flourished on the reef. Algæ, corals, alcyonarians, Foraminifera, and other forms of less importance contribute their remains to the building of the limestone, which may vary in composition as the life upon it varies. Corals may predominate in one place, algæ in another. Each reef must therefore be studied on its individual merits if its chemical character is to be understood. Precipitated carbonates, whether of bacterial origin or not, must also be taken into account, and their quantity may be large. At Funafuti, where the limestone has been studied with unusual thoroughness, the order of importance of the leading organisms is estimated by A. E. Finckh,[8] as follows:

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[1] Compt. Rend., vol. 144, pp. 437, 1240, 1907.

[2] Idem, vol. 156, p. 732, 1913.

[3] See Cotte, J., Soc. de biologie, Compt. rend., vol. 55, p. 139, 1903; Bradley, H. C., Jour. Biol. Chemistry, vol. 3, p. 151, 1907; idem, vol. 8, p. 237, 1910.

[4] Am. Jour. Physiology, vol. 14, p. 313, 1905.

[5] Zeitschr. physiol. Chemie, vol. 33, p. 417, 1901.

[6] Philos. Trans., vol. 155, p. 203, 1865.

[7] Zeitschr. physiol. Chemie., vol. 72, p. 401, 1911; idem, vol. 86, p. 340, 1913.

[8] The atoll of Funafuti, pp. 125–150, London, The Royal Society, 1904.

1, *Lithothamnion;*[1] 2, *Halimeda;* 3, Foraminifera; 4, the corals, including *Heliopora* and other alcyonarians and the millepores. Here the corals are subordinate to the algæ, and even the Foraminifera outrank them. To call the Funafuti rock a coralline limestone would therefore be somewhat misleading.

Chemical analysis, however, is not the only factor of importance in determining the composition of a marine limestone. The crystalline character of the shells and skeletons, whether calcitic or aragonitic, must also be considered. For this purpose the well-known reaction with cobalt nitrate, the "Meigen reaction," is commonly employed, especially by W. Meigen himself, who has studied a considerable number of organisms, both recent and fossil, and some of his determinations[2] relate to genera examined by us. For these, excluding fossil forms, the data are as follows:

Calcite.	*Aragonite.*
Lithothamnium. Alga.	Halimeda. Alga.
Lithophyllum. Alga.	Galaxaura. Alga.
Polytrema. Foraminifer.	Millepora. Hydromedusa.
Corallium. Alcyonarian.	Distichopora. Hydromedusa.
Tubipora. Alcyonarian.	Heliopora. Alcyonarian.
Serpula. Annelid.	Spirula. Cephalopod.
Terebratula. Brachiopod.	Sepia. Cephalopod.
Argonauta. Cephalopod.	
Balanus. Crustacean.	

Of these genera, so far as they have been studied chemically, all in the aragonite column are almost completely nonmagnesian. The trifling amounts of magnesia which they contain may be due to impurity or to alteration. Two in the calcite column, *Terebratula* and *Balanus*, are also nonmagnesian, and the others are all rich in magnesium carbonate. Meigen also tested twenty zoantharian corals, all aragonitic and nonmagnesian, and a considerable number of mollusks. Some of the molluscan shells were aragonitic and some were calcitic, but all except *Argonauta* were nearly free from magnesia. One echinoderm in Meigen's list, of a genus not represented in our series of analyses, was calcitic, and so too were ours. All the echinoderms, so far as we know, are distinctly magnesian. In short, it seems probable, in the light of existing evidence, that all aragonitic organisms are essentially nonmagnesian; and that those characterized by the presence of much magnesia are calcitic. Many calcitic forms, however, are practically free from magnesia. The general relation thus brought out is very suggestive. Magnesium carbonate associates itself only with calcite, with which it is isomorphous, rather than with aragonite of different crystalline form, but why some organisms should secrete calcite and others aragonite in building their shells or skeletons is as yet unexplained, although the difference may be of physiologic origin, and may perhaps be correlated with differences of structure.

The considerations presented in the preceding pages bear directly upon the problem of the origin of marine dolomite. We now know what classes of organisms supply magnesia to the limestones and something also of what may be called their mineralogic nature. The dolomite ratio between the two carbonates is, however, never directly reached; there is always at first a large excess of calcium over magnesium, and a mixture is formed instead of the true double salt. To produce dolomite the original limestone must either be enriched by magnesia derived from sea water or else concentrated by leaching away of lime; furthermore, its two component carbonates must be somehow forced to combine. These processes may be operative simultaneously, but it is more probable that the change from magnesian limestone to dolomite is brought about by a series of steps, taken one at a time.

In this connection the report on Funafuti, already cited, is remarkably suggestive. On that atoll or island a committee of the Royal Society put down a boring 1,114 feet, in limestone all the way. The rock throughout contained organic remains and was studied both

[1] The term *Lithothamnion* as used in the Funafuti report is general, and includes not only *Lithothamnium*, but also *Lithophyllum*, *Goniolithon*, and perhaps other genera. See Atoll of Funafuti, p. 332, London, The Royal Society, 1904.

[2] Naturf. Gesell. Freiburg Ber., vol. 13, p. 40, 1903.

microscopically and chemically. At a depth of 4 feet from the surface it cont cent of magnesium carbonate, and at 15 feet 16.4 per cent. To this point a by leaching is indicated, even if not absolutely proved, and it is probable that soluble nonmagnesian aragonitic structures had been in part at least dissolve unstable aragonite is more easily dissolved than calcite, a relation so well establisl not need to be discussed here.[1] The fact that many sections of the core are desc ernous" in structure is additional evidence that solution had occurred. Solutio by the carbonic acid generated during the decomposition of the organic matter of and through its agency calcite would be dissolved also. Magnesium carbonat readily removed.

At a depth of 25 feet the core contained 16 per cent of magnesium carb specimen examined consisted largely of *Lithothamnion* remains, which accounts sition. On the other hand, the core at 40 feet carried only 5.85 per cent of magr ate and was in great part composed of *Heliopora* and *Millepora*, both originally The core sections evidently varied in composition according to the variations in from which they were formed. A sample taken only a few feet away from the have had a different composition. Some fluctuations in the series of analyses ma for in this way.

Below 40 feet the magnesian content of the rock diminished rapidly, point to 0.79 per cent of magnesium carbonate. Between 40 and 637 feet the the rock was about that of an ordinary limestone, but at the latter depth cryst began to appear.[2] At 640 feet the percentage of magnesium carbonate was increased, with some fluctuations, to the final depth of 1,114 feet. At 950 feet per cent and at the lowest depth it was 41.05 per cent. From 640 feet downwar essentially dolomite, although it contained an excess of calcite. Pure dolomite per cent of magnesium carbonate, a figure that was very nearly approached.

The column of rock represented by the Funafuti boring thus appears to be three fairly definite zones. The surface layer is about 25 feet thick, and its directly determined by the organisms living above it. In this zone the evide tration by leaching is quite clear. From 25 feet down to 640 feet the rock i limestone, with very little magnesia. The lowest zone, from 640 feet downwar and the dividing line between this and the limestone above is very distinct. the proportion of magnesium carbonate in the rock rises from 2.44 to 26.33 per

To account for all the differences in the Funafuti column does not fall wi of this investigation, even if it were possible to explain them. Possibly the lii middle zone was laid down during a period when nonmagnesian organisms much more abundant than they are now. This supposition, however, does n the sudden change from limestone to dolomite in passing from the second to th

In order to partly explain these changes we venture to offer some pur suggestions, believing that speculation is legitimate if it tends to stimulate inve provoke a closer scrutiny of existing evidence.

The lowest portion of the Funafuti rock is, of course, the oldest, and it cont of *Lithothamnion* and other organisms which flourish abundantly only at mo Magnesia was then concentrated in the rock, in part directly from living forn by leaching, as at present. The thickness of the rock shows that it must have during a long period of depression, which may have submerged the island to a few of the magnesian organisms, especially the algæ, could thrive. A prolonged of equilibrium, then followed, during which very little rock was formed, and much of the dolomitization took place.

The period of rest was succeeded by one of elevation, which brought the again to the surface, when reef building began anew, but with relatively fe

[1] This leaching at Funafuti has already been pointed out by J. W. Judd in The atoll of Funafuti, p. 384
[2] See the petrographic report by C. G. Cullis in The atoll of Funafuti, pp. 392–420.

organisms than formerly. Between 552 and 660 feet the nonmagnesian *Halimeda* is the main constituent of the cores. The new rock, then, was less magnesian than the older, and the sharp break between the two zones becomes intelligible. Magnesian organisms were not extinct, for their remains appear throughout the Funafuti cores, but they were much less abundant than at first. Whether this supposition is true or not might be determined by a quantitative study of the thin sections of the rock, which ought to be still in existence. The published records of them seem to be purely qualitative, except in so far as they indicate the frequency of occurrence of the different organisms. They do not show their relative quantities.[1] At present magnesian organisms predominate and their composition is reflected in the composition of the surface limestone.

Our assumptions regarding changes of sea level at Funafuti are not altogether imaginary. In their report upon the geology of the island T. W. E. David and G. Sweet[2] assert that—

> the surface geological evidence collected by us proves, in our opinion, that several oscillating vertical movements of the above have taken place in the immediate past at Funafuti, and we should not, therefore, be surprised if the evidence gained from the core shows that movements of the shore line in both directions have occurred at Funafuti at earlier epochs.

The chemical and algal evidence reinforce the physiographic evidence. On the formation of "coral reefs" during subsidence or elevation there is an abundant literature, which we can not attempt to summarize. We are dealing with a specific instance from a single point of view. The subject is one over which there has been much controversy. Our principal assumption, which may or may not be sustained, is that the dolomitic zone at Funafuti represents an old reef upon which the present reef is superimposed. A similar basing of new reefs upon older ones has already been pointed out by T. Wayland Vaughan.[3]

On many other islands in the South Pacific dolomitized limestones which were originally reefs are found at elevations hundreds of feet above sea level. A number of these rocks have been described by E. W. Skeats,[4] who made good series of chemical analyses of them and also discussed their origin. Organic and especially algal remains were common in the rocks and were clearly recognizable in spite of the fact that in many places they had been much altered by the process of dolomitization. In these islands an elevation of the land had clearly taken place. Similar limestones from the Fiji, Tonga, Paumotus, and Ladrone islands have been studied by R. L. Sherlock,[5] who found them to be composed in great part of algal and foraminiferal remains. Among 47 thin sections which he examined, "*Lithothamnion*" was found in 35, *Polytrema* in 21, echinoderm fragments in 17, and corals in 15. In short, all the evidence goes to prove the importance of the algæ as limestone builders and the subordinate character of the corals. This importance is now fully recognized by students of marine limestones and by paleontologists generally.

It is not our purpose to discuss the origin of dolomite in general, for probably the rock originates in more than one way.[6] At Funafuti, however, and at other similar localities marine organisms have much to do with its origin, and that phase of the dolomite problem may appropriately be considered here. The first step in the process, concentration by leaching, has already been described, but that is only a beginning. The living organisms, plant or animal, contain much less magnesia than is required to form dolomite, and its quantity must be increased from some outer source. That source, or at least the only source which we can discover, is found in ocean water, in which magnesium is much more abundant than calcium. This source has been recognized by many authorities, and it is generally assumed that an exchange may occur between the magnesium of the water and the calcium of the limestones, the one replacing the other. This assumption is due to J. D. Dana,[7] who sought to explain the dolomitization of a limestone on the island of Makatea.

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[1] The atoll of Funafuti, tables on pp. 336–361.
[2] Idem, p. 88.
[3] Papers from the Tortugas laboratory of the Carnegie Institution of Washington, vol. 5, p. 66, 1914.
[4] Idem, vol. 42, p. 51, 1903.
[5] Mus. Comp. Zool. Bull., vol. 38, p. 349, 1903.
[6] For a rather full summary of the subject see Clarke, F. W., The data of geochemistry, 3d ed., U. S. Geol. Survey Bull. 616, pp. 559–571, 1916.
[7] Corals and coral islands, 3d ed., p. 393 [1890].

That an enrichment in magnesia from sea water is possible is shown by some experiments made by C. Klement,[1] who found that a concentrated solution of magnesium sulphate and sodium chloride, at 90° C., attacked aragonite and corals strongly, yielding a mixture of carbonates containing as high as 41.9 per cent of magnesium carbonate. Calcite, on the other hand, was but slightly altered. In the light afforded by these experiments the nonmagnesian aragonitic organisms assume new importance, and are perhaps more influential in the production of dolomite than the distinctly magnesian species. Their solubility is evident in the first stage of magnesian concentration; their alterability is effective in the second.

Klement's experiments, however, were performed with concentrated solutions and at a rather high temperature. Under natural conditions, with less concentration and at lower temperatures, the same reaction may take place very slowly but be equally complete in time. Years, or even decades, may be needed to effect such changes as were produced in the laboratory within 48 hours. In the study of geochemical processes the time factor must always be taken into account.

So far, according to Klement, a mixture of the two carbonates has been found. To convert them into the double carbonate, dolomite, another step must be taken, and here again time may be important. A porous rock has been produced, which is saturated with water and buried at a depth which subjects it to considerable pressure. If the two carbonates of calcium and magnesium were perfectly dry, pressure alone would probably not effect their union, but under the influence of moisture, with slight solution going on at the surfaces of the solid particles, there would be a degree of molecular mobility which might bring about combination. This is probable, although so far as we know it has not been actually proved. The establishment of the facts ought not to be beyond the range of experimental investigation. Views similar to ours relative to the formation of dolomite have already been advanced by Général E. Jourdy, who especially recognizes the importance of the algæ, of aragonite, and of time. Much remains to be done, however, before the problem of dolomitization can be completely solved.[2]

On the subject of phosphate rock we have little to say. We have shown that several groups of organisms are rich in phosphates, but the extent of their contributions to the sediments is uncertain. At best they can at first form beds of only moderately phosphatic limestone, which may perhaps be concentrated by the leaching away of the excess of carbonates. Vertebrate skeletons are also phosphatic and may possibly be more important additions to the sediments than invertebrate remains. In some localities limestones have been phosphatized by percolations from beds of guano,[3] but that process is not one which needs to be considered here. It has no relation to the present research.

In the course of our investigation we have made one very curious discovery, to which we have repeatedly called attention, namely, the fact that in certain groups of organisms the proportion of magnesium carbonate is dependent upon or determined by temperature. The crinoids and alcyonarians show this relation very clearly, and it is also suggested by our analyses of Foraminifera, crustaceans, and algæ. As a rule the organisms from warm waters are much richer in magnesia than those from cold waters, and the observed differences are often strikingly conspicuous. This rule, or rather tendency, we are inclined to believe is general, although we must admit that there are probably exceptions to it. Whether the increase in magnesia in passing from cold to warm regions is absolutely regular or not we do not venture to say, but apparent irregularities may be due to any one of several different causes. Slight analytical errors, uncertainty as to exact temperatures, impurities in the specimens analyzed, and differences in the concentration of sea water may all help to produce irregularities, which, however, are not likely to be large. The salinity of ocean water is very variable; it is 3.5 per cent in the great ocean, 4 per cent on the southern shores of the Mediterranean, and less than 1

[1] Min. pet. Mitt., vol. 14, p. 526, 1894. See also Pfaff, F. W., Centralbl. Mineralogie, 1903, p. 659, and Neues Jahrb., Beilage Band 9, p. 485, 1894. Two separate papers.

[2] Soc. géol. France Bull., 4th ser., vol. 14, p. 279, 1914.

[3] In The data of geochemistry: U. S. Geol. Survey Bull. 616, pp. 519–528, 1916, a summary of our knowledge of phosphate rock may be found.

per cent in the Baltic, differences that are great enough to exert some influence upon the vital processes of marine animals. Although the ratio between calcium and magnesium is practically constant in all oceanic waters, a concentrated water would contain more magnesium, volume for volume, than a water that was more dilute. Whether an organism living in a concentrated water would assimilate more magnesia because of its enriched environment no one can say, but conceivably it might do so. The influence of temperature might in that way be slightly modified. This is only a suggestion, not a statement of established fact. That warmth favors the assimilation of magnesia by marine invertebrates seems to be reasonably certain, but why it should be so is not clear. The relation is definite but as yet unexplained. We hope it is not inexplicable.

Attempts will probably be made to use our data in studies of climatology, but are such attempts likely to be fruitful? The question is not easy to answer. At a first glance it would seem as if warm regions should be more favorable to the formation of magnesian limestones than cold regions, but the evidence is by no means conclusive. A dense population of cold-water organisms might add more magnesia to the sediments than a sparse population of warm-water forms. The massiveness of the animals must also be considered. The alcyonarian *Paragorgia arborea*, as its specific name indicates, grows to treelike dimensions, but its skeleton contains only about 9 per cent of magnesium carbonate. Tropical alcyonarians are much richer individually in magnesia, but they are not so large. One *Paragorgia* would therefore count for more than many smaller alcyonarians in the formation of magnesian limestone. If, however, the warm-water organisms are as abundant as the cold-water forms, and if their aggregate mass is as great, then the tropical limestones of marine origin should be more richly magnesian than those from higher latitudes. The determination of the facts we must leave to zoologists.

In conclusion we must express our thanks to the officers of the United States National Museum and the Geological Survey who have aided us by furnishing authentic material for our investigations. Messrs. Paul Bartsch, Austin H. Clark, William H. Dall, W. L. Schmitt, and T. Wayland Vaughan have all been most generous with their services. Dr. Marshall A. Howe, of the New York Botanical Garden, has also been most kind in supplying us with algæ. Without the help of these friends our research would have been impossible.

○

DEPARTMENT OF THE INTERIOR
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Professional Paper 103

BRACHYCERATOPS

A CERATOPSIAN DINOSAUR FROM THE TWO MEDIC FORMATION OF MONTANA

WITH NOTES ON ASSOCIATED FOSSIL REPTILES

BY

CHARLES W. GILMORE

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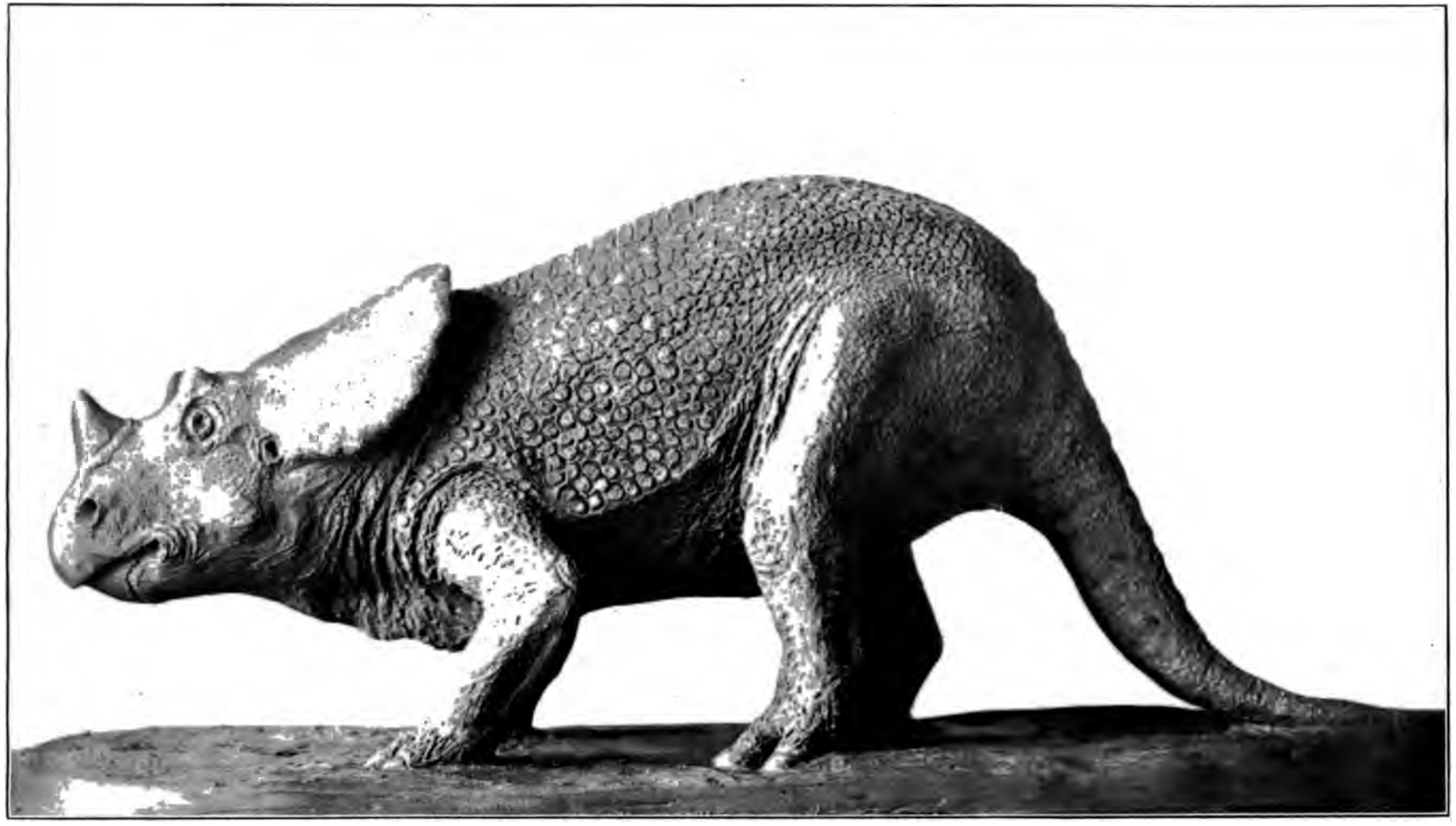

LIFE RESTORATION OF BRACHYCERATOPS MONTANENSIS.
Modeled by Charles W. Gilmore. About one-eighth natural size.

BRACHYCERATOPS, A CERATOPSIAN DINOSAUR FROM THE TWO MEDICINE FORMATION OF MONTANA, WITH NOTES ON ASSOCIATED FOSSIL REPTILES.

By CHARLES W. GILMORE.[1]

INTRODUCTION.

The fossils on which this paper is based were collected by me and my assistant, Mr. J. F. Strayrer, during the summer of 1913, while working under the auspices of the United States Geological Survey on the Blackfeet Indian Reservation, in northwestern Montana. The specimens were obtained from exposures of the Two Medicine formation along Milk River near the Canadian boundary, in T. 37 N., R. 8 W., about 30 miles northwest of the town of Cut Bank, Mont., and along Two Medicine River in T. 31 N., R. 7 W., about 15 miles southwest of Cut Bank. Vertebrate remains were found at these places in 1911 and 1912 by Eugene Stebinger, while he was engaged in Geological Survey work, and he was the first to note that the localities are good fields for finding specimens of fossil vertebrates.[2] Although the present collection is small, it is of considerable scientific interest because it supplements the collections made in neighboring areas by other investigators, and because it contains a new genus of Ceratopsia in addition to other recognizable specimens which afford evidence that considerably extends the geologic and geographic ranges of forms heretofore described.

The beds from which the collection was made constitute the upper part of the Two Medicine formation, which includes the equivalent of the Judith River formation and some older beds. The fossiliferous beds are also the equivalent of the upper part of the Belly River formation as found in neighboring areas of Canada.

The fauna of the American Judith River formation, although diversified, is very inadequately known. Many of the genera and species have been founded on specimens so scant and fragmentary that it is almost impossible to refer to them subsequently discovered and more perfect materials. Recent collections made by L. M. Lambe, of the Canada Geological Survey, and by Barnum Brown, of the American Museum of Natural History, from the Belly River formation along Red Deer River in Canada, however, have placed this fauna on a more solid basis.

The purpose of this paper is to give as complete and detailed a description of the skeletal anatomy of *Brachyceratops montanensis* as the material at hand will permit and to discuss briefly, in systematic order, other forms represented by specimens in the collection made in 1913.

I take this opportunity to express my thanks for assistance rendered and for courtesies extended at many times, both in the field and during the preparation of this report, by Messrs. M. R. Campbell, T. W. Stanton, and F. H. Knowlton, and especially by Mr. Eugene Stebinger, all of the United States Geological Survey.

STRATIGRAPHY OF THE TWO MEDICINE FORMATION.

By EUGENE STEBINGER.

All the vertebrate fossils described in this report were collected from a single formation of Montana (Upper Cretaceous) age, to which the name Two Medicine formation has been applied recently by the United States Geological Survey. It occurs throughout the part of the plains

[1] Assistant curator of fossil reptiles, United States National Museum.

[2] Stebinger, Eugene, Washington Acad. Sci. Jour., vol. 4, p. 383, 1914.

region in Montana that lies at the east base of the Lewis Range and the mountains immediately to the south. The formation is well exposed in all the larger stream valleys, and at many places along those streams it is carved into intricate badlands. (See Pl. II, *A*.) The rocks are soft and light colored, white to gray and greenish gray being the prevailing tints, and are chiefly clay, clay shale, and soft sandstone. The sandstones are very irregular in thickness, thinning rapidly in short distances, and in places are strongly cross-bedded, being in part at least of eolian origin. Thin beds of red clay and thin nodular limestones are occasionally found. The formation averages 2,000 feet in thickness and is very uniform in appearance throughout, except that its lowest 250 feet is more sandy than its upper part.

Besides a remarkable abundance of vertebrate remains, the fossils in the Two Medicine formation include both invertebrates and plants. The invertebrates, according to T. W. Stanton, are principally fresh-water types, and *Unio*, *Viviparus*, and *Campeloma* are the most abundant genera. Brackish-water forms are also frequently found, especially in the lower sandy portion. Fossil wood, some of it in complete sections of tree trunks as much as 18 inches in diameter, is abundant. The flora so far collected is reported by F. H. Knowlton to be of Belly River age. The evidence of rapid and irregular deposition afforded by the lithology of the formation, together with the presence of a dinosaur fauna, of land plants, and of fresh-water shells, leaves little doubt that the rocks as a whole are continental in origin.

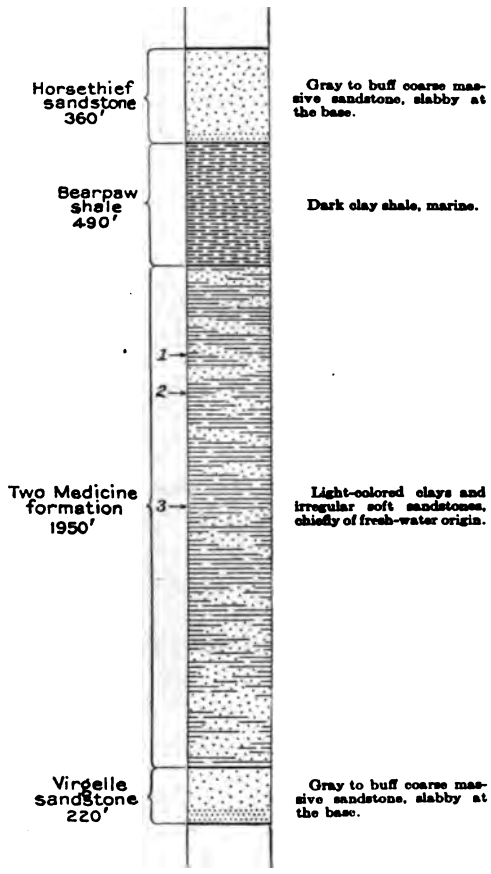
Horsethief sandstone 360′
Gray to buff coarse massive sandstone, slabby at the base.
Bearpaw shale 490′
Dark clay shale, marine.
1
2
Two Medicine formation 1950′
3
Light-colored clays and irregular soft sandstones, chiefly of fresh-water origin.
Virgelle sandstone 220′
Gray to buff coarse massive sandstone, slabby at the base.

FIGURE 1.—Generalized section of the formations of the Montana group (Upper Cretaceous) in northwestern Montana. Arrows indicate position of horizons in Two Medicine formation from which most of the vertebrates described in this report were collected.

Fortunately, the stratigraphy of the Two Medicine formation and the formations associated with it can be very easily deciphered, because of the simplicity of the nearly horizontal structure and the general excellence of the exposures throughout large areas of the Montana group in northwestern Montana. The fact that the Two Medicine formation lies below one marine clay shale carrying a Pierre fauna and above another marine shale carrying an upper Colorado fauna is well established. According to recent work[1] the section of the Montana group, including the Two Medicine formation, as exposed on Two Medicine River between its mouth and Family post office, contains four lithologic units, which have been designated Virgelle sandstone, Two Medicine formation, Bearpaw shale and Horsethief sandstone. (See fig. 1.) The Colorado shale, carrying a characteristic marine fauna, underlies this group of formations and appears in the section at the mouth of Two Medicine River under bold cliffs of Virgelle sandstone. Traced northward the Virgelle sandstone and Two Medicine formation prove to be exactly equivalent to the Belly River beds as mapped by Dawson[2] in southern Alberta. Dawson recognized the prominent sandstone at the base of the Belly River formation and described it in detail but not as a separate formation. In Montana this basal sandstone has been traced over a large area in the western part of the State and has everywhere been recognized as a distinct mappable unit. This made it impossible to use Dawson's designation Belly River for any of the rocks in Montana, and the name Two Medicine was therefore adopted for the upper part of Dawson's original formation. On the other hand, the relations of the Judith River formation to the Two

[1] Stebinger, Eugene, Washington Acad. Sci. Jour., vol. 4, p. 383, 1914.
[2] Dawson, G. M., Canada Geol. Survey Progress Rept. for 1882–1884, p. 112c, 1885.

A. BADLANDS ON MILK RIVER ABOUT 30 MILES NORTHWEST OF CUT BANK, MONT.

Looking south across secs. 27 and 28. T. 37 N., R. 8 W. *a*, Place where large trachodont femur was found; *b*, place where Hypacrosaurus skeleton was found; x–x, clay zone, filled with minute shell fragments. Photograph by Eugene Stebinger.

Medicine formation became apparent on tracing the formations eastward toward the type area of the Judith River formations in central Montana. The Judith River formation proves to be equivalent to only the upper part of the Two Medicine formation, which in its entirety is equivalent to the upper part of the Eagle, the Claggett, and the Judith River formations combined.

The stratigraphic positions of the three principal horizons in the Two Medicine formation at which the fossils here described were obtained are indicated by arrows on the columnar section. (See fig. 1.) All the vertebrate remains collected in 1913 were obtained from the upper half of the formation, so that the base of the overlying marine shale, the Bearpaw, was the most convenient datum for fixing the stratigraphic position of the fossil localities. This upper part of the Two Medicine formation is very fossiliferous, bone fragments being abundant throughout the strata and no well-marked zonal distribution being apparent. For the sake of stratigraphic accuracy three horizons at which most of the specimens were collected are described below, without implying that the distribution of these fossils is at all limited to these horizons. Horizon No. 1, at which *Brachyceratops montanensis* and *Hypacrosaurus altispinus*? were collected on Milk River in T. 37 N., R. 8 W., lies 340 feet below the base of the Bearpaw shale as exposed on the slopes of Landslide Butte on the south edge of this township. In the N. ½ sec. 27 the beds at this horizon lie immediately above a zone of clays about 10 feet thick filled with minute shell fragments (see X–X, Pl. II, *A*), apparently mainly Unios, which serves as an excellent marker for the bone bed above it, from which *Brachyceratops* and *Hypacrosaurus* were collected. This shell zone can be traced for about half a mile northwestward, to a point where the river valley turns abruptly northward, and is marked throughout by abundant fossil bones. All the specimens of *Brachyceratops montanensis* were found 1½ miles north of this locality (see Pl. II, *C*), on the strike of the gently westward-dipping beds, at nearly the same elevation and therefore at approximately the same stratigraphic position. Horizons 2 and 3, at which material was collected on Two Medicine River in T. 31 N., R. 7 W., were fixed stratigraphically by measuring downward from the base of the Bearpaw shale as exposed 6 miles to the west. Horizon 2, at which an unidentified trachodont (No. 7955, U. S. N. M.) was collected on the south side of Two Medicine River in the NE. ¼ sec. 15 (see Pl. II, *B*), is about 490 feet below the Bearpaw shale. Horizon 3, which yielded a trachodont on the south side of the river, but in the NE. ¼ sec. 12 (No. 8058, U. S. N. M.), is 445 feet lower, being approximately 935 feet below the same shale and therefore very near the center of the Two Medicine formation.

FAUNA OF THE TWO MEDICINE AND RELATED FORMATIONS.

Vertebrate fossils are found throughout the upper part of the Two Medicine formation, and nearly all of them belong to the class Reptilia. The great number of trachodonts found appears to indicate that these were the most abundant dinosaurs of the epoch. Their remains are distributed from the base to the very top of the beds representing the upper half of the Two Medicine formation, as exposed in the localities visited in 1913 along Milk and Two Medicine rivers. On each of the 15 days spent in prospecting 8 to 14 specimens sufficiently complete to be recognized as pertaining to the Trachodontidae were discovered. Only a few of these, however, were perfect enough to warrant collecting, and none were intact, though many found in the Edmonton and Belly River areas in Canada and in the Lance formation of Wyoming and Montana were still articulated.

Next to the Trachodontidae the Ceratopsidae were most abundant, but of the half a dozen specimens found only one (the type specimen of *Brachyceratops montanensis*) is of scientific interest, the others consisting either of single bones or of fragments so badly weathered as to be of little value. They show, however, the existence here of large members of the group.

Armored dinosaurs were present in these localities, as indicated by the finding of the dermal plates of a member of the Ankylosauridae, provisionally referred to the genus *Euoplocephalus*.

Teeth of carnivorous dinosaurs are common, but skeletal remains appear to be rare, except as single bones. It would appear from the scant evidence that several small dinosaurs of which little is known lived at this time.

Fragments of turtles are plentiful, but no complete shells were observed. The soft-shelled kinds appear to predominate. A few teeth and single bones of extinct crocodiles were found, but only two vertebral centra of the long-snouted rhyncocephalian reptile *Champsosaurus*, which is abundant in some areas of the Belly River formation.

Isolated scales and plates of ganoid fishes, probably referable to the genus *Lepisosteus*, were found here and there throughout the beds.

The genera and species identified from this small collection from the Two Medicine formation are as follows:

Ceratopsidae:
- Brachyceratops montanensis Gilmore.
- Ceratopsian, gen. and sp. undet.

Trachodontidae:
- Hypacrosaurus altispinus? Brown.
- Stephanosaurus marginatus? (Lambe).
- Trachodont, gen. and sp. undet.
- Trachodont, gen. and sp. undet.

Ankylosauridae:
- Europlocephalus sp.

Rhyncocephalia:
- Champsosaurus sp.

Chelonia:
- Basilemys sp.
- Aspideretes foveatus (Leidy).
- Aspideretes sp.

Crocodylidae:
- Leidyosuchus sp.

Pisces:
- Lepisosteus sp.

The vertebrate fauna of the Two Medicine formation, as represented by this small collection, although too meager to serve as a basis for close comparisons with related faunas, accords with the stratigraphic evidence for the correlation of the upper part of the Two Medicine formation with the dinosaur-bearing beds of the Judith River and Belly River formations. This is shown not so much perhaps by identity of forms as by the primitive facies of the fauna as a whole, and also by the similarity in degree of development of some of the principal representatives of the Dinosauria. The latter statement is especially applicable to members of the family Ceratopsidae. In order to make this assertion a little clearer, it may be well to review briefly the development of the Ceratopsia.

The earliest ceratopsians known were found in the Judith River and Belly River formations. The group occurs also in the Edmonton and in the upper part of the Lance.

In contrasting the ceratopsians from these formations the chief differences are found in the structure of the skull, especially in the comparative sizes of the postorbital and nasal horn cores and in the open or closed structure of the nuchal frill. In the Judith River, Belly River, and Two Medicine ceratopsians the nasal horn is usually the larger, whereas the postorbital horns are small, rudimentary, and sometimes wanting. In the Lance ceratopsians the opposite condition is universal. The fenestrated frill is a feature of all the earlier ceratopsians, but is retained in the Lance forms only by *Torosaurus* and in lesser degree by *Diceratops*, all others having a complete bony frill without fenestration.

The earliest known Ceratopsia may be contrasted with those from the Lance formation as follows: (1) The individuals are smaller, (2) the nasal horn core is usually larger than the postorbital horn cores, (3) the nuchal frill is imperfectly developed, (4) the postfrontal and dermosupraoccipital bones are less perfectly united, (5) the squamosals are shorter, and (6) the dentition is reduced.

With all these primitive characteristics the single known Two Medicine genus *Brachyceratops* is in exact accord. In addition it may be said that *Brachyceratops montanensis* appears to have its closest affinity with *Monoclonius*[1] *dawsoni* Lambe from the Belly River of Canada.

Previous to 1913 only three recognizable genera of the Ceratopsidae (*Monoclonius*, *Ceratops*, and *Centrosaurus*) were known from the Judith River and Belly River formations. Since 1913, however, the discovery of new material has more than doubled the number of described genera, Lambe having established the genera *Styracosaurus*,[2] *Chasmosaurus*,[3] *Eoceratops*,[4] and *Protoro-*

[1] Since this observation was made (1914) Lambe has referred his species to *Brachyceratops* (Lambe, L. M., On *Eoceratops canadensis*, gen. nov., with remarks on other genera of Cretaceous horned dinosaurs: Canada Geol. Survey Mus. Bull. 12, Geol. ser., No. 24, p. 18, May 7, 1915).

[2] Lambe, L. M., A new genus and species of Ceratopsia from the Belly River formation of Alberta: Ottawa Naturalist, vol. 27, pp. 109–116, pls. 10–12, 1913.

[3] Lambe, L. M., On *Gryposaurus notabilis*, a new genus and species of trachodont dinosaur from the Belly River formation of Alberta, with a description of the skull of *Chasmosaurus belli*: Idem, p. 155, pls. 19, 20, February, 1914.

[4] Lambe, L. M., op. cit. (On *Eoceratops canadensis*, etc.), pp. 1–25.

saurus,[1] from the Belly River of Canada, and *Brachyceratops*[2] having been added from the Two Medicine formation of Montana. Sufficient material of *Brachyceratops* was obtained to permit a skeletal restoration. (See Pl. IV.)

Recent explorations in the Edmonton formation show that these beds have a characteristic ceratopsian fauna, regarded by Brown[3] as being intermediate between that of the Judith River and Belly River formations on the one hand and that of the Lance formation on the other hand, with affinities nearer those of the former. The fact that a number of specimens from the Edmonton of Canada are as yet undescribed renders it impracticable at this time to make a close comparison of this fauna with those of the formations named. It should be mentioned, however, that none of the ceratopsian genera of the Judith River, Belly River, or Two Medicine formations are known to have continued into either the Edmonton or the Lance.

As stated previously, the trachodont reptiles were the most abundant dinosaurs of the Judith River, Belly River, and Two Medicine formations, and recent discoveries have shown them to be almost as diversified in their structure as the contemporary ceratopsians.

If the genera *Saurolophus*, *Hypacrosaurus*, *Stephanosaurus*, and *Kritosaurus* and the five species described since 1910 are included, no less than 15 genera and 25 species of North American Trachodontidae have been described. The list as known in 1902, however, consisting of 10 genera and 20 species, should be greatly reduced. Hatcher[4] favored the retention of only two genera, *Claosaurus* and *Trachodon*, considering that the remaining eight were synonyms of *Trachodon*. *Claosaurus* he would restrict to the single species from the Niobrara formation of Kansas. The finding of more perfect material, however, has shown that several of the species formerly referred to *Trachodon* represent distinct genera and that Hatcher's proposed reduction was too radical. Of the several genera established on good specimens it appears very likely that some will yet prove to be synonyms of earlier-described genera founded on fragmentary material, but this can be determined only by careful comparison of all the type specimens. Until such a revision is made few of the earlier described forms will be of use in correlation or in working out the phyletic or other relations of the group. Hatcher was probably correct in restricting *Claosaurus* to the single species from the Niobrara formation. It is unfortunate, however, that his opinion that the genus *Trachodon* should include species from the Judith River to the close of the Lance has become so widely accepted by vertebrate paleontologists. In the first place, the type species of the genus (*Trachodon mirabilis* Leidy) came from the Judith River formation and was founded on inadequate material, consisting of "specimens of teeth generally very much worn and in a fragmentary condition," with which it is wholly impossible positively to identify better specimens discovered subsequently. That Hatcher later realized this fact is clearly shown by his statement that "Although the trachodonts are easily distinguished by their teeth from the other Dinosauria of these beds (Judith River), it is scarcely possible to identify the various species of this genus or the genera of the family from the teeth alone."[5]

Even though it may eventually be found that *Trachodon* can be placed on a sound footing, there is reason for believing that the genus is not present in the Lance,[6] as shown by the less number of teeth in all the known specimens from the Judith River, Belly River, and Two Medicine formations.

In the Lance trachodonts, several complete dentaries of which are included in the United States National Museum collections, the rows of teeth vary from 52 to 57. All the Judith River, Belly River, and Two Medicine trachodont dentaries in the collections have fewer rows, varying in number from 39 to 46. The same difference exists in the few maxillae available. It thus

[1] Lambe, L. M., On the fore limb of a carnivorous dinosaur from the Belly River formation of Alberta, and a new genus of Ceratopsia from the same horizon, with remarks on the integument of some Cretaceous herbivorous dinosaurs: Ottawa Naturalist, vol. 27, pp. 131–135, pl. 14, January, 1914.

[2] Gilmore, C. W., A new ceratopsian dinosaur from the Upper Cretaceous of Montana, with note on *Hypacrosaurus:* Smithsonian Misc. Coll., vol. 63, No. 3, pp. 1–10, pls. 1–2, 1914.

[3] Brown, Barnum, Cretaceous correlation in New Mexico, Wyoming, Montana, and Alberta: Geol. Soc. America Bull., vol. 25, p. 374, 1914.

[4] Hatcher, J. B., The genera and species of the Trachodontidae (Hadrosauridae, Claosauridae) Marsh: Carnegie Mus. Annals, vol. 1, p. 385, 1902.

[5] Stanton, T. W., and Hatcher, J. B., Geology and paleontology of the Judith River beds: U. S. Geol. Survey Bull. 257, pp. 96–97, 1905.

[6] Gilmore, C. W., On the genus *Trachodon:* Science, new ser., vol. 41, pp. 658–660, 1915.

seems that the earliest known trachodonts, like the more primitive ceratopsians, have fewer teeth, so that now it may be safely asserted that one of the marked phases in the specialization of the members of this group in successive geologic periods is the progressive increase in the number of teeth in the dental magazines.

The genus *Trachodon* is based on specimens from the Judith River formation, and its smaller number of teeth would indicate that it did not persist into the later formations. It appears to me, therefore, that *Trachodon* should either be treated as an indeterminate genus or at the most should be restricted to Judith River species. Such restriction would leave the Lance specimens now referred to *Trachodon* without generic designation, unless by a study of the type specimens one of the older generic terms can be revived.

The geologic range of the Trachodontidae is considerably greater than that of the Ceratopsidae, commencing in the Niobrara and continuing through the Judith River, Belly River, Two Medicine, Edmonton, and Lance formations. They disappear, like the Ceratopsidae, at the close of the Lance.

Four genera, *Hypacrosaurus*, *Kritosaurus*, *Stephanosaurus*, and *Trachodon*, are now recognized as occurring in the Judith River and Belly River formations, and two of them, *Hypacrosaurus* and *Stephanosaurus*, have been identified in the collection from the Two Medicine formation. *Hypacrosaurus*[1] was described originally from the Edmonton of Alberta, Canada, and *Kritosaurus*[2] from beds in New Mexico described by Brown as the Ojo Alamo formation. Brown[3] has recently shown the generic identity of the *Gryposaurus* of Lambe, from the Belly River, with the *Kritosaurus* of Brown, and the suggestion is made that as "other reptilian remains are of the primative facies the Ojo Alamo beds may well be of Judith River age."

In a recent paper[4] Brown has shown that the family Trachodontidae may be divided naturally into two groups, those of one having a crested skull and a footed ischium; and those of the other lacking the crest and having a slender ischium without distal expansion. Members of the first group are so far known only from the Belly River, Two Medicine, and Edmonton formations, whereas representatives of the second group are present in all formations as well as in the Judith River and the Lance.

Little can be said at this time of the progressive changes that have taken place in the structure of the Trachodontidae, though it appears that the dental magazine of the Lance trachodonts contains a greater number of teeth than that of the trachodonts from the Judith River, Belly River, and Two Medicine formations. The presence of four digits in the pes of the Judith River genus *Pteryopelyx* would appear to indicate a foot more primitive than that of the three-toed Lance trachodonts.

Both the theropodous or flesh-eating dinosaurs and the armored dinosaurs are so little known that at present it is impossible to make adequate comparison between the species of different horizons. Representatives of the theropodous group, however, are present in all the formations discussed in this paper, and the study of specimens now at hand will doubtless show the progressive changes that have taken place in their skeletal structure and thus will be an aid in the future correlation of the separated formations.

The rhyncocephalian reptile *Champsosaurus* has a wider geologic range than any other of the extinct reptilian forms, except of course some of the chelonian genera. Remains of *Champsosaurus* have been found in the Judith River, Belly River, Two Medicine, Edmonton, Lance, Puerco, and Fort Union formations. It is likely that when better material is known the species will be found to vary in successive formations, but this fact can not now be determined.

The crocodiles are represented in the Belly River formation by the single identifiable genus *Leidyosuchus*, a genus that continues into the Lance, as shown by the type specimen of *Leidyosuchus sternbergii* from the Niobara County area in Wyoming. Isolated teeth and bones from the Two Medicine formation are provisionally identified as pertaining to this genus.

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[1] Brown, Barnum, A new trachodont dinosaur, *Hypacrosaurus*, from the Edmonton Cretaceous of Alberta: Am. Mus. Nat. Hist. Bull., vol. 32, pp. 395–406, 1913.

[2] Brown, Barnum, The Cretaceous Ojo Alamo beds of New Mexico, with description of the new dinosaur *Kritosaurus*: Am. Mus. Nat. Hist. Bull., vol. 28, pp. 267–274, 1910.

[3] Sinclair, W. J., and Granger, Walter, Paleocene deposits of the San Juan Basin, N. Mex.: Am. Mus. Nat. Hist. Bull., vol. 33, p. 303, 1914.

[4] Brown, Barnum, Cretaceous-Eocene correlation in New Mexico, Wyoming, Montana, Alberta: Geol. Soc. Am. Bull., vol. 25, pp. 355–380, 1914.

The turtles are represented in the collection made in 1913 from the Two Medicine formation by only two identifiable specimens. One of these, *Basilemys* sp., is of interest as having its nearest affinity with *B. nobilis* Hay, from the beds in New Mexico to which Brown has applied the name Ojo Alamo, thus apparently corroborating the dinosaurian evidence on which the Belly River formation was correlated with the beds at Ojo Alamo.

The fish *Lepisosteus* has a wide geologic range and is valueless as a horizon indicator.

In conclusion it may be briefly stated that the fauna of the Two Medicine formations, as represented by this one small collection, is on account of its primitive facies in accord with the stratigraphic evidence for the correlation of these beds with the dinosaur-bearing beds of the Judith River and Belly River formations. Taken as a whole the faunas of the equivalent formations are undoubtedly ancestrally related to those of the Lance, for, with one exception, all the families represented in these older formations are present also in the Lance.

Notwithstanding the fact that certain of the earlier faunal lists seem to indicate that several genera and species of reptiles persisted from Belly River to Lance time, the evidence that has been gradually accumulating in recent years indicates beyond question that the fauna of the Judith River and Belly River formations is distinctly more primitive than the related forms in the Lance, although a few of the more persistent types, such as *Champsosaurus*, *Leidyosuchus*, and some turtle genera, pass from one formation to the other.

DESCRIPTIONS.

Family CERATOPSIDAE Marsh.

Brachyceratops montanensis Gilmore.

Plates I, III, IV; text figures 2–9, 11–26, 28–39, 41–47.

Brachyceratops montanensis Gilmore, Smithsonian Misc. Coll., vol. 63, No. 3, pp. 1–10, pls. 1–2, 1914.

Type of genus and species.—A considerable portion of a disarticulated skull (No. 7951, U. S. N. M.), showing nasals, prefrontals, postfrontals, postorbitals, premaxillaries, maxillaries, lachrymal, alisphenoid, and exoccipital. With this is provisionally associated a fragmentary part of the frill, a right dentary, and a predentary.

Type locality.—NE. ¼ sec. 16, T. 37 N., R. 8 W., Milk River, Blackfeet Indian Reservation, Teton County, Mont.

Paratypes.—Rostral and portions of the premaxillaries (No. 7952, U. S. N. M.); sacrum, pelvis, articulated caudal series of 50 vertebrae continuous to the tip of the tail (No. 7953, U. S. N. M.), with which are provisionally associated dorsal vertebrae and ribs; tibia, fibula, and partly articulated hind foot from the left side, consisting of an astragulus, calcaneum, and 2 tarsals of the distal row, 4 metatarsals and a portion of a fifth, and 11 phalanges (No. 7957, U. S. N. M.).

Paratype locality.—Same as that of the type.

Generic and specific characters.—Typically of small size. Skull with facial portion much abbreviated and deep vertically. Supraorbital horn cores small and firmly united with postorbitals. Nasal horn core outgrowth from nasals, large, slightly recurved, laterally compressed, and divided longitudinally by median suture. Frill with comparatively sharp median crest, fenestrae apparently of small size, and entirely within the median element. Border of frill scalloped but without separate marginal ossifications. Dentition as compared with *Triceratops* greatly reduced. Five digits in the pes, the fifth being vestigial. Ilium with greatly expanded anterior blade that curves strongly outward.

The specimens.—The specimens of *Brachyceratops* on which the present description and restoration are based were found on Milk River within a small rectangular area of about 6 by 7 feet. (See Pl. II, *C*.) With the exception of two hind feet and three series of caudal vertebrae, one of which (No. 7953; Pl. III, *A* p. 20) was entire and articulated with the sacrum and closely associated with the pelvic bones and femora, all the skeletal parts were disassociated and too closely intermingled to show to which individuals they belonged.

The proper association of the bones of the different individuals was rendered still more difficult by the fact that all the specimens were of approximately the same size. Comparison of portions of no less than nine ischia showed that at least five individuals were present, and it is quite possible that there were one or two more. In the type (the disarticulated skull, No. 7951) the sutures interlocked so perfectly as to leave no doubt that the assembled elements belonged to the same cranium.

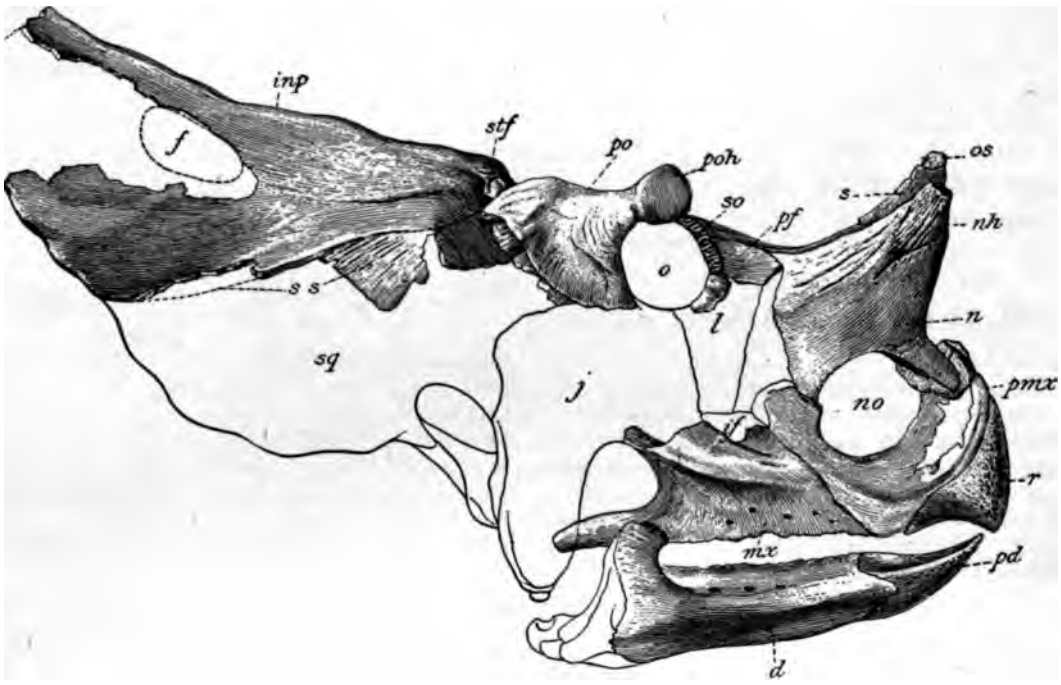
OSTEOLOGY OF BRACHYCERATOPS.

THE SKULL.

'eneral features.—When found the skull was entirely disarticulated, but the excellent vation of the bone and the absence of distortion rendered the assembling and correct lation of the scattered elements comparatively easy. This specimen is of the utmost tance in the proper interpretation of the cranial elements, especially of those parts of the psian cranium that are now somewhat in controversy.

'he type of the genus and species, as was stated, is small. This statement is true so far as d to the known specimens, but it should be added that to some extent the small size of specimens may be due to immaturity. The open sutures of the skull, sacrum, and verte- ll testify to the youth of the individuals.

'he facial portion of the skull is greatly abbreviated, as compared with that of the ceratop- of the Lance formation. (See fig. 2.) It is to this shortening that the generic name refers.



.—Skull of *Brachyceratops montanensis* Gilmore. Type. No. 7951, U. S. N. M. One-third natural size. Lateral view. *d*, Dentary; estra in frill; *if*, infraorbital foramen; *inp*, interparietal; *j*, jugal; *l*, lachrymal; *mx*, maxillary; *n*, nasal; *nh*, nasal horn cores; *no*, anterior l opening; *o*, orbit; *os*, ossicle on top of nasal horn core; *pd*, predentary; *pf*, prefrontal; *pmx*, premaxillary; *po*, postorbital; *poh*, post- al horn core; *r*, rostral; *s*, suture separating halves of nasal horn; *sq*, squamosal; *so*, sutural border on prefrontal for small supraorbital; tural surfaces for squamosal; *stf*, supratemporal fossa.

arial opening, as in other known Judith River and Belly River forms, is well forward and the nasal horn, whereas in the later and more highly specialized *Triceratops* this orifice is ly posterior to that horn. The distance between the nasal and supraorbital horns is ex- gly short, owing largely to the shortened nasal bones, the great fore and aft development basal portion of the nasal horn, and the forward position over the orbits of the small brow

he exact pitch of the frill portion in relation to the anterior part of the skull can not be rely determined. In figure 2 it has been placed in accordance with the evidence of articu- skulls.

n entirely new phase of nasal horn development and one which appears to be unique dinosaurs appears in the longitudinal separation of the horn core into two halves by the suture. The nasal horn itself appears to be an outgrowth from the nasal bones instead of originated from a separate center of ossification, as in the more specialized *Triceratops*.

It appears quite probable that some of the described Belly River species will be found to show a similar mode of nasal horn development when juvenile specimens are found.

There is no trace of an epinasal bone such as was found by Lambe [1] in *Eoceratops*, and the curved groove on the *Brachyceratops* horn which suggested to Lambe the upper boundary of the epinasal ossification appears to be only one of the vascular grooves.

Nasals.—The nasals are especially deep and massive, owing to the development on their superior surfaces of the nasal horn cores. Posteriorly they present a pointed process with a beveled underlapping surface for contact with the prefrontals (the frontals and lachrymals of authors). Laterally they send down a deep extension to meet the premaxillary, and anteriorly the arched ventral borders of the nasal bones from the upper half of the boundary of the narial orifice. Anteriorly they send out vertically flattened processes (*p*, fig. 4) between which are received the ascending processes of the premaxillae. These nasal processes appear to end about 32 millimeters in advance of the forward line of the horn core, so that the upper outline of the beak is formed largely by the premaxillaries. The horn has a broad fore and aft extent at its

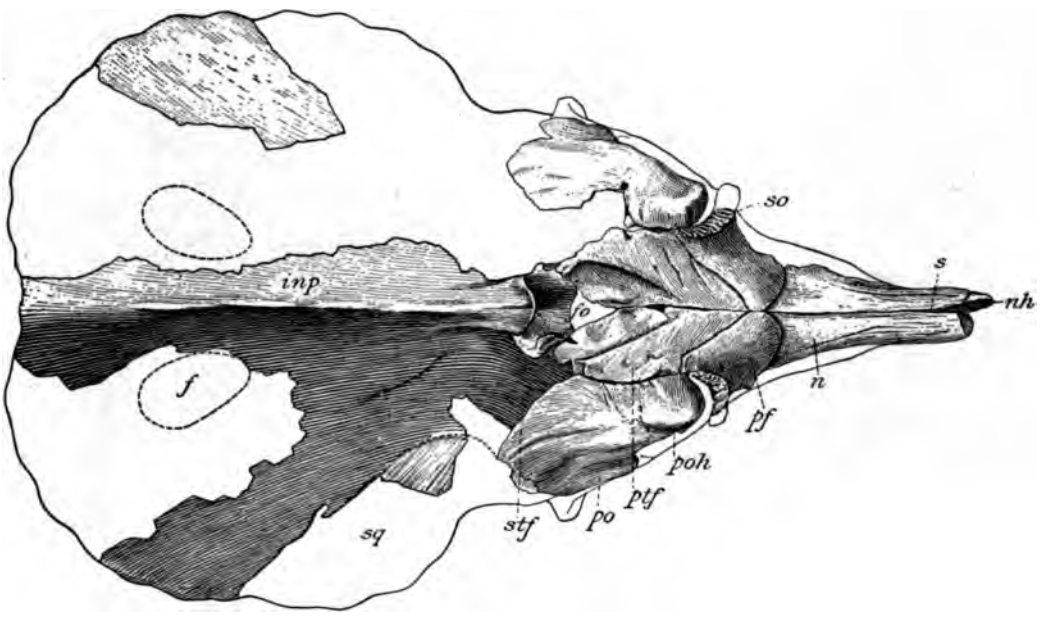


FIGURE 3.—Skull of *Brachyceratops montanensis* Gilmore. Type. No. 7951, U. S. N. M. One-third natural size. Superior view. *f*, Fenestra in frill; *fo*, postfrontal foramen; *inp*, interparietal; *n*, nasal; *nh*, nasal horn core; *pf*, prefrontal; *po*, postorbital; *poh*, postorbital horn core; *ptf*, postfrontal; *s*, suture representing halves of the nasal horn core; *so*, sutural border for missing supraorbital bone; *sq*, squamosal; *stf*, supratemporal fossa.

base but tapers sharply to a blunt, moderately high point. Transversely it is much compressed at the base, though inclined to expand somewhat toward the summit. The horn as a whole is directed somewhat forward, but the curve of the posterior side is such as to give the impression that its upper part is slightly recurved. The surfaces of the upper half are roughened and grooved by vascular impressions.

On the left half of the nasal horn, at the apex, a small, flattened oval ossicle (*os*, fig. 4) rests in a shallow depression or pit. This ossicle is distinct from the underlying bone and may represent the incipient horn of later ceratopsians, in which it is known to be developed from a center of ossification distinct from the nasal bones.

Prefrontals.—The prefrontals (the frontals and lachrymals of authors) are deeply emarginate anteriorly and receive between them the pointed posterior ends of the nasals.

The prefrontal is a quadrangular plate of bone diagonally placed so as to fill the interspace between the postfrontal and nasal bones. Its thickened posterior end contributes to the inner part of the anterior boundary of the orbit. (See *o*, fig. 5.) Near the posterior termination on the

[1] Lambe, L. M., On *Eoceratops canadensis* gen. nov., with remarks on other genera of Cretaceous horned dinosaurs: Canada Geol. Survey Mus. Bull. 12, p. 7, 1915.

external side a narrow vertical sutural surface (*so*, fig. 2) was for the articulation of the small supraorbital bone, which is missing. This element would have completed the thickened orbital border which projects immediately in front of the eye and which forms so conspicuous a feature of the ceratopsian skull. On the upper posterior end of the prefrontal a pointed peglike projection is received in a corresponding pit in the anterior border of the postfrontal, thus strengthening the union of these two bones. The prefrontal is just barely in contact with the postorbital at the base of the postorbital horn core.

Postfrontals.—The true extent of the postfrontals in the ceratopsian skull is here correctly determined for the first time. Authorities have heretofore considered the postfrontal as extending from the median line outward and including all of that portion of the skull here designated as postfrontal and postorbital. (See fig. 3.) In this specimen a longitudinal suture just internal to the base of the supraorbital horn core divides the so-called postfrontal into two

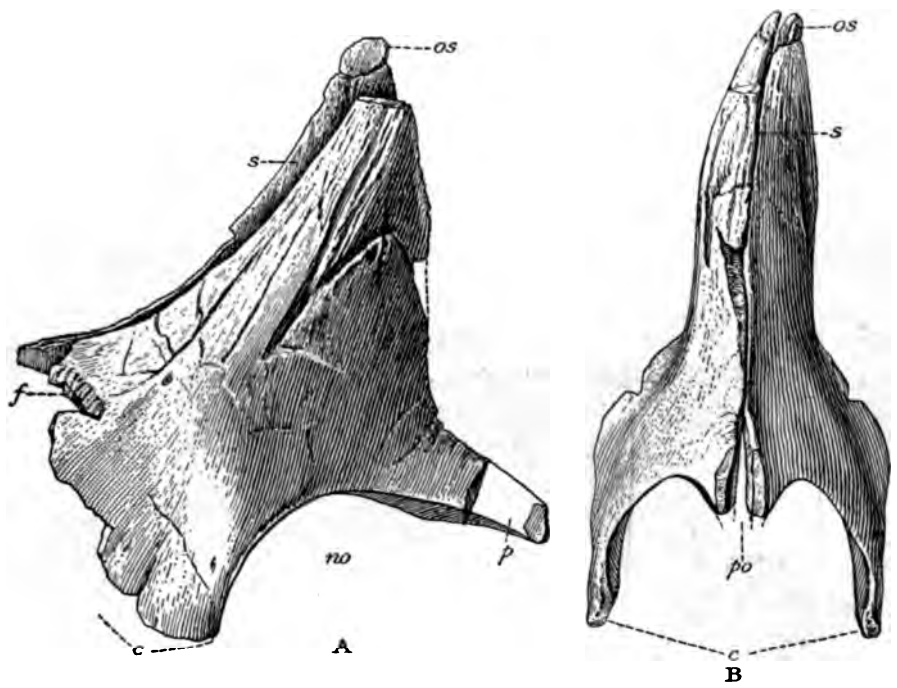


FIGURE 4.—Nasals and nasal horn cores of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. One-half natural size. A, Side view; B, front view. *c*, Surface for contact with the premaxillaries; *f*, surface for articulation of prefrontal; *no*, anterior nasal opening; *os*, bony ossicle on top of horn core; *p*, anterior process of nasal; *po*, orifice for superior processes of premaxillaries; *s*, suture separating two halves of nasal horn.

distinct elements. The inner portion all paleontologists agree in calling the postfrontal; the outer appears without question to represent the postorbital. Von Huene [1] in 1912 regarded the portion forming the posterior boundary of the orbit in a skull of *Triceratops prorsus* as representing the whole of the postorbital, but the writer questions the correctness of this determination in the genus *Triceratops*.

In *Brachyceratops* the postfrontal is a somewhat irregularly triangular bone, longer than wide, which unites by suture on the median line with its fellow of the opposite side. (See fig. 6.)

Anteriorly the combined postfrontals terminate in a pointed projection interposed between the deeply emarginate posterior borders of the prefrontals. Posteriorly and on either side of the postfrontal foramen these bones articulate by suture with the median element of the frill. A toothed external border unites with the postorbital. Beginning between the horn cores the median upper surfaces of the postfrontals are angularly depressed, gradually deepening and widening transversely as they approach the postfrontal foramen, much as in *Styracosaurus albertensis* Lambe.[2]

[1] Huene, Friedrich von, Beiträge zur Kenntnis des Ceratopsidenschädels: Neues Jahrb., 1912, Band 2, fig. 3, p. 151.

[2] Lambe, L. M., A new genus and species of Ceratopsia from the Belly River formation of Alberta: Ottawa Naturalist, vol. 27, No. 9, pl. 2 *B*, 1913.

The relation of the prefrontals and postfrontals in *Brachyceratops* is unusual, for in most dinosaurian crania the frontal is interposed between them, the relation shown in *Brachyceratops* being found elsewhere, so far as the writer is aware, only in *Stegosaurus* among the Dinosauria and in some of the Permian Reptilia. Von Huene has shown (correctly, the writer believes) that the frontal in *Triceratops* has been entirely excluded from the dorsal surface of the skull.

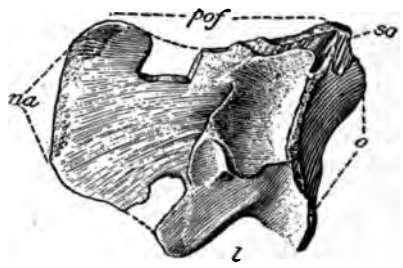
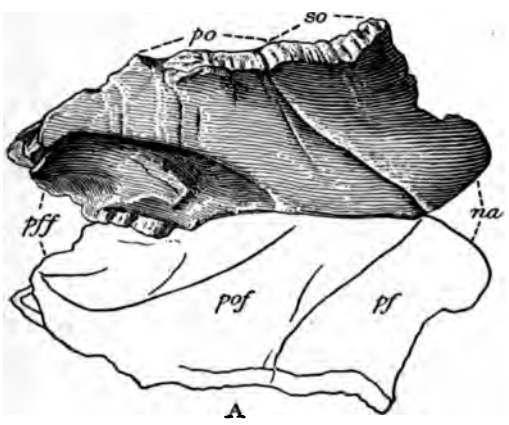


FIGURE 5.—Right prefrontal of *Brachyceratops montanensis*. Type. No.7951, U.S. N.M. Three-fourths natural size. Internal view. *l*, Side opposed to the lacrymal; *na*, side articulating with nasal; *o*, orbital border; *pf*, side articulating with the right postfrontal; *so*, supraorbital border.

Postorbital.—The postorbital gives rise to the small supraorbital horn core and forms nearly one-half of the orbital border. Posterior to this horn, which is situated on the extreme anterior end, the bone flares into a wide expanded portion, much deflected externally, with a curved posterior border, the inner half forming a portion of the outer boundary of the supratemporal fossa and the outer half having an underlapping sutural edge for articulation with the squamosal. The straight inferior edge meets the jugal, which is missing in this specimen.



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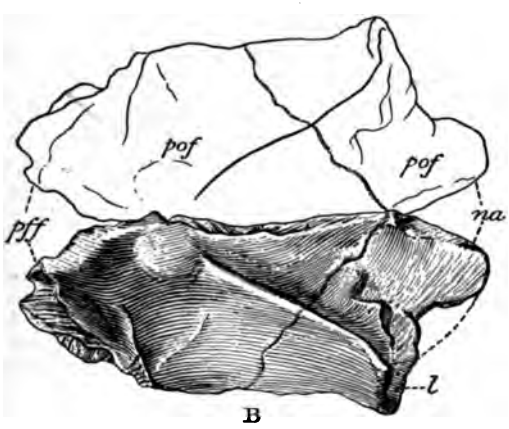

B

FIGURE 6.—Postfrontals and prefrontals of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. One-half natural size. A, Superior view; B, inferior view. *l*, Pit for reception of peg on the lachrymal; *na*, notch between prefrontals which receives posterior ends of nasals; *pf*, prefrontal; *pff*, postfrontal foramen; *po*, postorbital border; *pof*, postfrontal; *so*, supraorbital border.

The thickened anterior border shows a sutural edge for union with the missing supraorbital bone. On the median inferior surface is a shallow pit which receives the outer end of the alisphenoid, as it does in *Stegosaurus*, *Camptosaurus*, and *Triceratops*. (See also *alsp*, fig. 7.)

Immediately above the orbit on the anterior part of the postorbital there rises a low horn core, whose upper extremity is obtusely rounded longitudinally (see *poh*, fig. 2) but is sharply pointed transversely. The external surface of this horn is plane, the internal strongly convex, with the antero-posterior diameter greatly exceeding the transverse. Its total height above the orbit is 31 millimeters. These horn cores appear to be outgrowths from the postorbital bones unless they include a posterior supraorbital element such as has recently been found in the skull of *Stegosaurus*.[1] The type specimen shows no trace of such an element, but its possible existence again raises the question of the proper designation of these horns, which have been called successively postfrontal and supraorbital horn cores. If they are outgrowths from the postorbital bone, as the present specimen appears to indicate, postorbital horn core would be the more appropriate designation.

Dermosupraoccipital.—The frill is represented by the median elements from two individuals. (Nos. 7950 and 7951, U. S. N. M.) Portions of each are missing, but the better-preserved specimen is provisionally associated with the type as shown in figures 2 and 3. This association, however, is only provisional in so far as it applies to the actual individual, for without question all the bones belong to the same kind of an animal.

[1] Gilmore, C. W., Osteology of the armored Dinosauria in the United States National Museum, with special reference to the genus *Stegosaurus*: U. S. Nat. Mus. Bull. 89, p. 33, 1914.

The dermosupraoccipital or interparietal, for as clearly shown by Hay [1] and Von Huene [2] it can not be the parietal, is united by suture with the anterior portion of the skull at the postfrontal foramen. The median part of the interparietal is sharply ridged except at the posterior extremity, where it flattens into a thinner portion with an emarginate median border. Between the fenestrae the median bar, in cross section, is triangular. (See fig. 8.) The superior surface of this ridge forward of its narrowest part between the fenestrae presents low longitudinal swellings arranged one in front of the other. Proximally the median portion is greatly compressed transversely into a short neck, forward of which it again widens into a much depressed end that articulates laterally with the postfrontals and with them forms the upper boundaries of the postfrontal foramen (*fo*, fig. 3). Between these two lateral portions the median surface is deeply concave and slopes downward to a heavy truncated border that in all probability was suturally united with the parietals (*ps*, fig. 9). In *Brachyceratops* at least, the parietal was entirely hidden in the dorsal aspect, and it is presumed that similar conditions obtained in *Triceratops*, although Von Huene was inclined to regard a small portion of the median part of the frill posterior to the postfrontal foramen in that genus as being parietal.

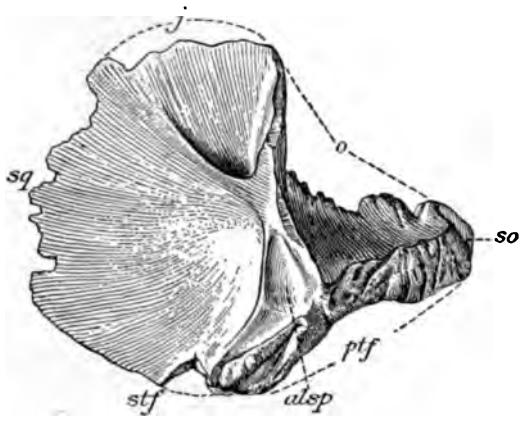

FIGURE 7.—Right postorbital of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. One-half natural size. Internal view. *alsp*, Pit for reception of outer end of alisphenoid; *j*, border in contact with the jugal; *ptf*, border in articulation with the postfrontal; *o*, orbital border; *so*, surface for articulation of supraorbital bone; *sq*, border for squamosal articulation; *stf*, free border contributing to the boundary of the supratemporal fossa.

The bone surrounding the frill fenestrae is very thin, but it thickens toward the lateral free edges and posteriorly. Proximally it remains thin where it forms the floor of the supratemporal fossae but thickens toward the sutural border for the squamosal (*sq*, fig. 9). The exact shape and extent of the frill fenestrae can not be accurately determined from the available specimens, but it is readily apparent that they were comparatively small. The surfaces of the frill are relatively smooth and lack the ramifying system of vascular grooves of the later ceratopsians. There were no epoccipital bones on the margins of the frill, but a series of prominences on either side of the median emargination give the periphery a peculiar scalloped effect much like that imparted by the separate ossifications of the *Triceratops* frills.

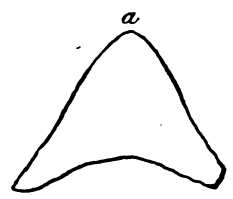

FIGURE 8.—Cross section of dermosupraoccipital of *Brachyceratops montanensis*. No. 7950, U.S. N.M. Three-fourths natural size. Taken posterior to middle of the bone. *a*, Crest of the frill.

Laterally the median portion unites with the squamosal by a straight sutural edge that is directed forward and inward toward the center of the skull. A triangular outward projection with an upper striated surface at the anterior termination of the squamosal suture represents a surface that was overlapped by the articulated squamosals (*ss*, fig. 2; *sq*, fig. 9). A low, sharp, diagonally directed ridge apparently indicates the posterior overlap of the squamosal. The squamosals are missing but appear, as in other primitive ceratopsians, to have been short and broad. (See fig. 10.)

Lachrymal.—Since the first description and illustrations of the species were published [3] a portion of the left lachrymal has been recognized, and it is shown in the corrected drawing of the skull (fig. 2).

In the type specimen only the orbital border remains, but this shows the orbit to be more nearly circular than was indicated in the first restoration of the skull. It articulates with the

[1] Hay, O. P., On the skull and the brain of *Triceratops*, with notes on the brain cases of *Iguanodon* and *Megalosaurus:* U. S. Nat. Mus. Proc., vol. 36, p. 97, 1909.

[2] Huene, Friedrich von, Beiträge zur Kenntnis des Ceratopsidenschädels: Neues Jahrb., 1912, Band 2, pp. 150–156, figs. 3, 4, 5, and 6.

[3] Gilmore, C. W., A new ceratopsian dinosaur from the Upper Cretaceous of Montana, with note on *Hypacrosaurus:* Smithsonian Misc. Coll., vol. 63, No. 3, 1914.

prefrontal on the outer border by a short, blunt, peglike projection which is received in a pit on the outer anterior border of the prefrontal. It would be scarcely in contact, if at all, with the supraorbital bone, which is missing in this specimen. It also shows that the supraorbital is triangular, the posterior end being especially heavy where it abuts against the postorbital at the base of the postorbital horn core. The forward extension of the lachrymal is missing.

Alisphenoid.—The alisphenoid of the left side is preserved, but like all other elements of the skull, was disarticulated in this specimen. In outline it is subtriangular, resembling closely the homologous element in the *Triceratops* skull. The outer extremity has a smooth-finished rounded

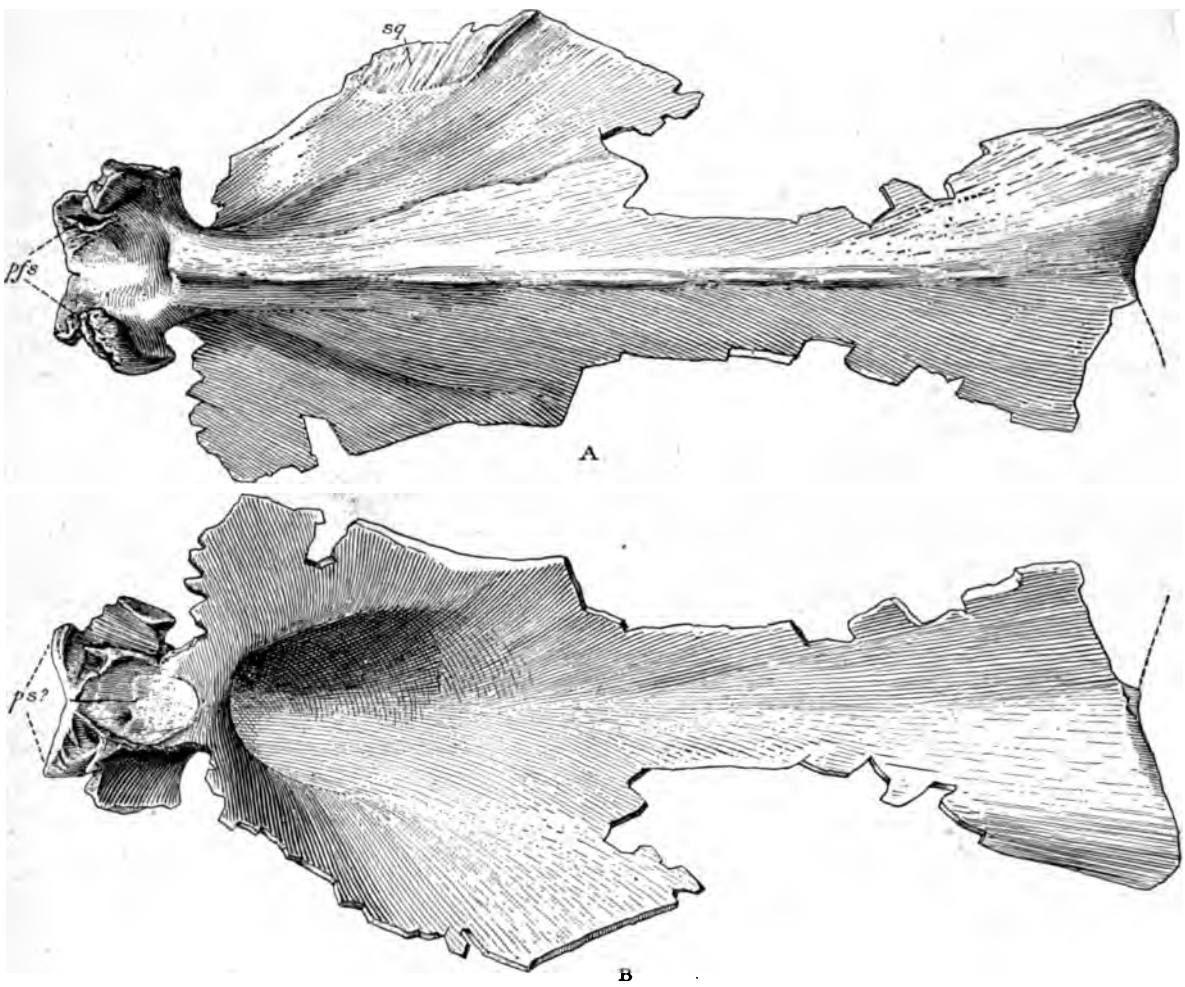

FIGURE 9.—Dermosupraoccipital or interparietal of *Brachyceratops montanensis*. No. 7950, U. S. N. M. One-half natural size. A, Dorsal view; B, ventral view. *pfs*, Borders that united with the postfrontals; *ps?*, borders that united with the parietal; *sq*, surface for overlap of squamosal.

end that is received in a pit on the ventral surface of the postorbital just posterior to the orbit at the base of the horn core. Posteriorly it presents a heavy sutural border that united with the prootic. Its inner portion is hollowed out and forms the wall of the portion of the brain case that lodges the cerebral hemisphere. As in *T. sulcatus* (No. 2416, U. S. N. M.), it has on its inner dorsal surface a sutural surface with which the parietal united. As in *Stegosaurus*, *Camptosaurus*, *Trachodon*, and *Triceratops*, the alisphenoid in *Brachyceratops* forms a portion of the anterior and inner boundaries of the supratemporal fossa. The border forming the boundary of the foramen ovale is broken in the specimen, but no doubt it is present in a perfect bone.

Exoccipital.—The front side of a somewhat fragmentary bone that is regarded as being the exoccipital from the left side of the skull is shown in figure 11. It was found in the float at some distance from the type specimen, but it is quite possible that it pertains to that individual.

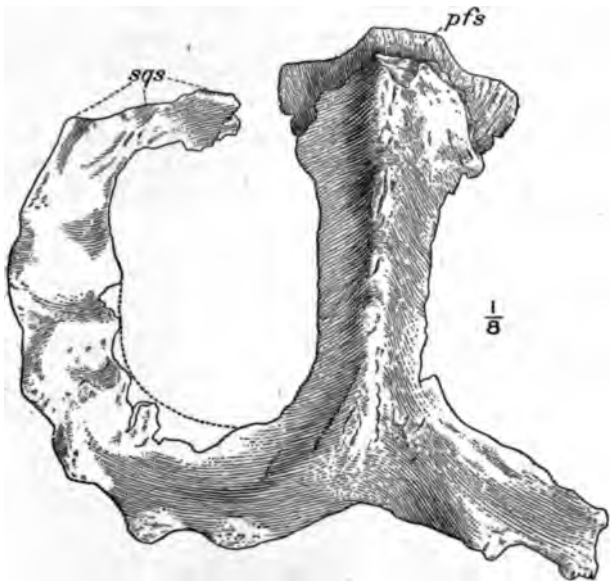

FIGURE 10.—Dermosupraoccipital of *Monoclonius crassus*. Type. No. 3398, American Museum of Natural History. One-eighth natural size. Superior view. *sqs*, Surface for articulation with squamosal; *pfs*, surface for postfrontal. (After Hatcher.)

The bone is flattened and platelike and has a broadly rounded external end or paraoccipital process that unites with the squamosal (*sq*, fig. 11). The inner end is cut off obliquely, with a toothed sutural border which articulates with the supraoccipital (*so*, fig. 11). On the lower internal angle of this end, seen best in posterior aspect, is a smooth concave surface which represents the upper portion of the exoccipital contribution to the boundary of the foramen magnum. The exoccipital of *Brachyceratops* corroborates Huene's determination [1] that in the Ceratopsia the supraoccipital enters the formation of the foramen magnum, as it does in many other dinosaurs, and is not excluded from it by the exoccipital, as determined by earlier authorities.

The pedical portion for articulation with the basioccipital is missing. On the anterior side, near the internal end, it is suturally roughened and diagonally ridged, presenting a surface for the overlapping of the outwardly directed process of the prootic (*pro*, fig. 11), as in *Triceratops*, *Camptosaurus*, and *Stegosaurus*. On the posterior side, near the lower border, is a sharp longitudinal ridge which fades out before reaching the external end; below this ridge, at the inner end, the entrance to the foramen ovalis occurs exactly as it does in *Triceratops serratus* Marsh, as determined by Hay.[2] The greatest length of this bone is 102 millimeters.

FIGURE 11.—Left exoccipital of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. One-half natural size. *pro*, Sutural surface for prootic; *so*, sutural border for supraoccipital; *sq*, end which meets the squamosal.

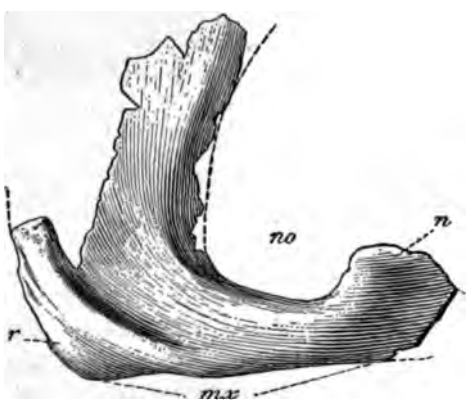

FIGURE 12.—Left premaxillary of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. One-half natural size. *mx*, Border uniting with the maxillary; *n*, border uniting with the nasal; *no*, anterior narial opening; *r*, surface over which the rostral laps.

Premaxillaries.—The premaxillaries of *Brachyceratops* are less massive and lack the lateral foramina found in those of *Triceratops*. They are compressed, thin bones and are closely applied to one another along the median line on the anterior half. Posteriorly they send backward and upward diverging processes with expanded posterior extremities that wedge between the maxillary and the descending branch of the nasal.

The median superior border of this part of the premaxillary is transversely rounded and forms the lower boundary of the anterior narial opening (*no*, fig. 12). All the premaxillae in the collection were badly mutilated before fossilization, and none of them have their anterior ascending portions complete. The best-preserved one (see fig. 12) exhibits a thin platelike ascending

[1] Huene, Friedrich von, Beiträge zur Kenntnis des Ceratopsidenschädels: Neues Jahrb., 1912, Band 2, pp. 148-150, fig. 2.

[2] Hay, O. P., On the skull and the brain of *Triceratops*, with notes on the brain cases of *Iguanodon* and *Megalosaurus*: U. S. Nat. Mus. Proc., vol. 36, p. 101, pl. 1, fig. 1, 1909.

process that is closely opposed to the one on the opposite side, the two rising to the nasals, where they are received in the deep groove (see fig. 4) at the base of the nasal horn core. It seems quite possible that the bony septum extends down farther into the narial opening from the base of the nasal bones than has been indicated in the restoration of the skull (fig. 2), resembling in this respect *Styracosaurus* (*Monoclonius*) *sphenocerus* (Cope).

There is no indication of an interpremaxillary fontanelle, as in *Triceratops*, and it appears probable that the opening through the premaxillaries (see fig. 2) would, if perfect, be a thin septum of bone extended from the narial border to the thickened anterior border over which the rostral articulates. The rostral does not extend so far back as in *Triceratops*, and the premaxillary therefore contributes more to the superior borders of the beak than it does in that genus.

Palatine foramina are also wanting in this specimen, though they are conspicuous in the palatal surface of all Lance ceratopsians.

Maxillaries.—The maxillaries are of irregular triangular outline, with alveoli in the functional row for 20 teeth—much fewer than in *Triceratops*, which has 40 alveoli. In the specimen all the functional teeth have fallen out, but two or more germ teeth remain and give some idea of their character. Posteriorly the maxillary is divided into two branches, an ascending process that articulates with the jugal (*js*, fig. 13), and an inferior horizontal branch that is relatively heavier than in *Triceratops*. On its superointernal side a longitudinal roughened border is overlapped by an anterior process from the pterygoid and is in contact with the palatine. Anteriorly and superiorly the maxillary has an extended articulation with the premaxillary (*pmx*, fig. 13). Between the premaxillary and jugal articulations the lachrymal and possibly the nasal were in contact with this bone. (See fig. 2.)

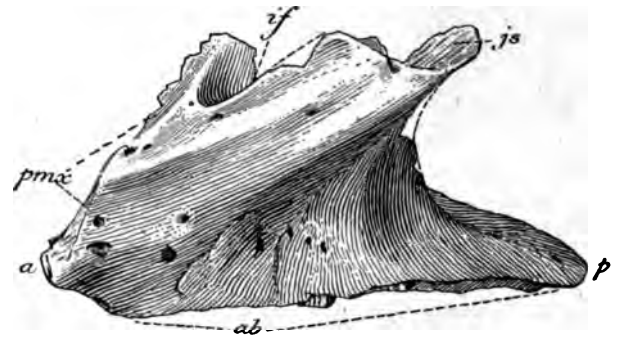

FIGURE 13.—Left maxillary of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. One-half natural size. A, External view; B, internal view. *a*, Anterior end; *ab*, alveolar border; *df*, dental foramina; *if*, infraorbital foramen; *js*, articulating surface for jugal; *p*, posterior end; *pmx*, groove for articulation with premaxillary.

On the anterointernal side a horizontal plate extends inward, meeting a similar projecting plate from the opposite maxillary on the median line, the inferior sides forming a portion of the forward palatal surface, as in *Triceratops*. The anterior half of the extended surface is perforated by a number of foramina, irregularly placed. On the internal side a curved row of 20 dental foramina (*df*, fig. 13, B), one to each dental groove, extends the entire length of the dental magazine.

The infraorbital foramen (*if*, fig. 13) occupies approximately the same position as in the *Triceratops* maxillary. The dental series occupies a longitudinal space of 155 millimeters. Internally the dental border is slightly concave from end to end.

The rostral.—The rostral is missing from the type, but is present in a slightly smaller individual (No. 7952, U. S. N. M.). (See fig. 14.) In general aspect it resembles the rostral of *Triceratops* but has a less curved anterior border. Externally the surfaces are pitted and grooved and in life were doubtless covered by a horny sheath.

Predentary.—The predentary (in fig. 15), except for its much smaller size, is indistinguishable from that of *Triceratops*. It is to be distinguished from the predentary of *Brachyceratops dawsoni* (Lambe) by the upward-turned apex of the anterior end.

Dentary.—The dentary is stout, gradually narrowing vertically toward the front, the anterior end being especially depressed and unusually broad transversely and being nearly at right angles to the posterior portion. Near the posterior end on the external surface a stout coronoid process (*c*, fig. 16) extends well above the dental border. It is compressed transversely but widens anteroposteriorly with a hooked forward process, as in other primitive ceratopsians. From its base a low, broad ridge extends forward at about midheight along the outer side of the dentary. Above and below this ridge the outer surface retreats obliquely inward.

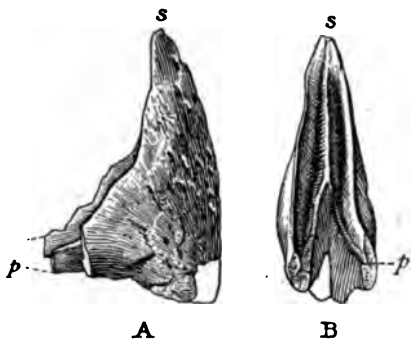

FIGURE 14.—Rostral of *Brachyceratops montanensis*. Paratype. No. 7952, U. S. N. M. One-half natural size. A, Side view; B, posterior view. *s*, Superior process; *p*, posterior processes.

Viewed from above (see fig. 17, B) the dental border is straight but is obliquely placed in relation to the lower portion—that is, it passes from the inner posterior margin to the outer anterior margin of the jaw. Beneath the coronoid process there is a deep mandibular fossa which extends forward about one-third the length of the dentary. On the inner side is the usual row of foramina (*df*, fig. 17) leading into the dental chamber. The exact number of alveoli can not be determined, but the tooth series is relatively shorter than in either *Ceratops* or *Triceratops*, probably not more than 17 dental grooves being present.

Teeth.—The dentition is represented by only a few germ teeth, the functional ones having fallen out before the jaws were entombed. That the teeth of *Brachyceratops* in both upper and lower jaws are much less numerous than those of *Triceratops* is indicated by a study of the maxillae and dentary. In *Brachyceratops* the maxillae have alveoli for 20 teeth and the dentary for 16 or 17, whereas in *Triceratops* the maxillae have more than 40, and the dentary 30 or more.

In the left maxillary of the type specimen the third tooth from the front is retained in position in the alveolus. (See fig. 18.) It is a young tooth and not fully erupted. A longitudinal keel divides its external surface into two unequal portions, the larger being anterior. The point of the crown posterior to the external keel is broken so that the contour of the crown is not known, but doubtless it is more pointed than is indicated in the drawing. The anterior border is finely serrated. On the inner side is a heavy keel, more centrally placed than that on the opposite side.

The lower dentition is represented by the crowns of two germ teeth (*t*, fig. 17) attached to the dentary. These germ teeth have a thin but very high median keel on the internal side. (See fig. 19.) The crown is pointed, as in all unworn ceratopsian teeth and its borders are serrated, those of the anterior border being finer than those of the posterior border. The alveolar border of the dentary measures 106 millimeters and the maxillary 155 millimeters. A detached tooth, supposed to pertain to the type, is shown in figure 20.

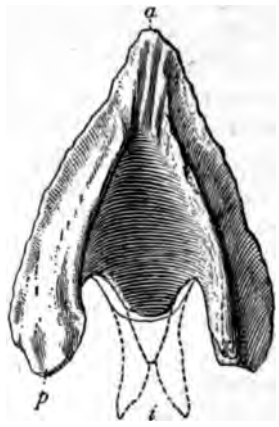

FIGURE 15 —Predentary of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. One-half natural size. Superior view. *a*, Anterior end; *p*, posterior end; *i*, inferior processes that underlap the dentary.

Supratemporal fossae.—The supratemporal fossae (*stf*, figs. 2, 3) open widely behind, as in all Edmonton and Belly River ceratopsians. These large excavations extend forward beneath the postorbital and postfrontal and laterally at its exit beneath the squamosal. These three bones form the roof as it were over the fossa, the upper boundaries of the fossa exit being formed by their sharp overhanging edges. The posterior floor of this fossa is formed by the smooth bone of the dermosupraoccipital or interparietal.

Hay [1] dissents from the generally accepted determination that these lateral openings in the ceratopsian skull represent the supratemporal fossae. He says: "It is difficult to under-

[1] Hay, O. P., On the skull and the brain of *Triceratops*, with notes on the brain cases of *Iguanodon* and *Megalosaurus*: U. S. Nat. Mus. Proc., vol. 36, pp. 97, 98, 1909.

stand how these bones became modified in such a way as to transfer the supratemporal fossae behind the paraoccipital processes of the exoccipitals. * * * These passages must represent the posttemporal fossae." He then proceeds to show that "the two supratemporal fossae have been pushed into one at the midline," having their exit through what other authorities have designated the postfrontal foramen.

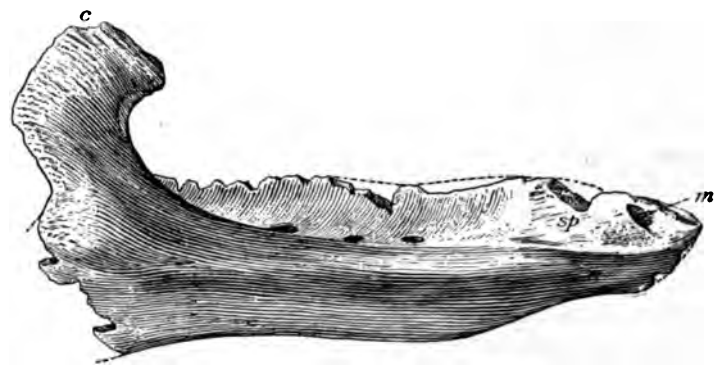

FIGURE 16.—Dentary of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. One-half natural size. External view. *c*, Coronoid process; *m*, mental foramen; *sp*, surface for overlap of predentary.

The position of the posterior exit of the supratemporal fossae behind the paraoccipital processes appears to be explained by the unusual posterior winglike development of the postorbital, which roofs the top of this fossa and thus carries its external exit back to the posterior free edge of that bone. Moreover, did they represent the post-temporal openings their exit would be below not above the dermosupraoccipital portion of the skull. That the vertical portion of the supratemporal fossa in the ceratopsian skull sustains its usual relations to the surrounding elements is clear. It has been determined that the alisphenoid in *Triceratops* and *Brachyceratops* has the same position and articulates with the same elements as in other dinosaurian skulls (*Stegosaurus*, *Camptosaurus*, *Diplodocus*, *Trachodon*, *Allosaurus*, and *Tyrannosaurus*). In other words, in all these forms the alisphenoid forms the wall of a portion of the brain case, turning outward and uniting at the external end with the postorbital and articulating posteriorly with the prootic and thus always forming the lower anterior boundary of the supratemporal fossa. If this fossa were continued upward in the ceratopsian skull it would open in its usual position on the superior surface of the skull at the posterior base of the postorbital horn core, and thus would be entirely in front of the paraoccipital processes; but, as stated, the roofing over of this region by the overlying bones carries its exit far posterior.

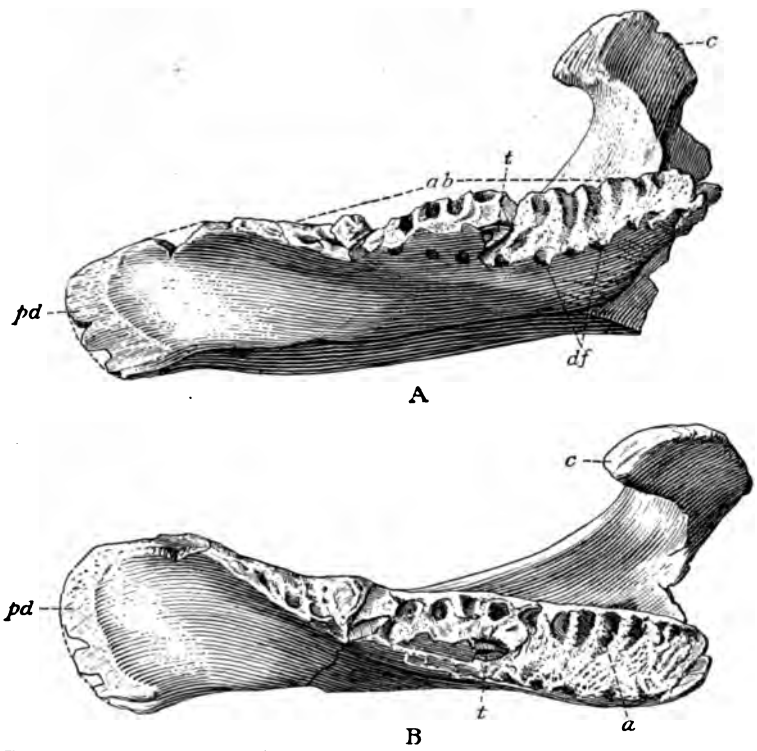

FIGURE 17.—Dentary of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. One-half natural size. A, Viewed internally; B, viewed from above. *a*, Alveolus; *ab*, alveolar border; *c*, coronoid process; *df*, dental foramina; *pd*, border for predentary; *t*, crown of an unused tooth (see fig. 19).

The modifications found in the ceratopsian skull are greater perhaps than in any other known group of reptiles, living or extinct. The chief specialization, as has been so clearly stated by Hatcher, is in the "direction of affording increased protection and in the development of more efficient organs for procuring food." The inclosed and compact nature of the skull was of the greatest value as a means of protection, and it contrasts strongly

with the open structure of most other dinosaurian skulls. These modifications have led to a rearrangement of the elements of the cranium, that until interpreted is as confusing as it is unusual. The bones of the skull become coossified early in life and thus still further add to the difficulties of interpreting their relationships.

The fortunate discovery of the skull of this juvenile specimen of *Brachyceratops*, taken in connection with the studies of Hay and Von Huene, clears up many of the doubtful points relating to the cranial anatomy that were so puzzling to earlier investigators. It now appears that the prefrontals and postfrontals, which in the normal reptilian cranium are lateral to the parietals and frontals, have in the ceratopsian skull pushed upward and inward above those bones, completely covering their dorsal aspect.

That the postfrontals were formerly separated is indicated in the Judith River and Belly River ceratopsians by the noncoalescence of their posterior borders, which in the later members of the Lance are always ankylosed. This brings up the question of the function of the "pineal fontanelle" of Marsh; the "postfrontal foramen" of Hatcher; the "postfrontal fontanelle" of Lull; the "supratemporal fossae" of Hay; and the "pseudopineal foramen" of Huene. All authorities, I think, are now agreed that it is not a pineal foramen and that it can not represent the combined supratemporal fossae as interpreted by Hay. The term "postfrontal foramen" is perhaps the most appropriate designation, for it is not, as suggested by Lull,[1] in any sense analogous to the fontanelle of human anatomy. Lull appears to

FIGURE 18.

FIGURE 19.

A

B

FIGURE 20.

FIGURE 18.—Third upper tooth of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. Twice natural size. External view. Found in place in the right maxillary.

FIGURE 19.—Unworn lower tooth of *Brachyceratops montanensis*. Type. No. 7951, U. S. N. M. Twice natural size. Internal view. Found in place in the right dentary. (See *t*, fig. 17.)

FIGURE 20.—Detached tooth of *Brachyceratops montanensis*. No. 7951(?), U. S. N. M. Twice natural size. A, External view; B, internal view.

be right, however, in saying that this opening transmits neither nerves nor blood vessels. It is probably only an opening not yet roofed by bone; in other words, the coalescence of the postfrontals with the dermosupraoccipital, which commenced prior to Two Medicine time had not been perfected in Lance time except in an occasional individual.

Measurements of the skull.—The following measurements, actual and estimated, were obtained from the type specimen:

Skull:	Millimeters.
Greatest length, about	565
Greatest breadth, estimated	400
Expanse of frontal region at base of brow horn cores	90
Greatest width of nasals	58
Length of interparietal along median line	315
Height of nasal horn core above border of narial orifice	125
Greatest width of postfrontals	80
Greatest length of combined postfrontals and prefrontals	126
Breadth between center of orbits	130
Postorbital horn cores at base:	
Anteroposterior diameter	34
Transverse diameter	27
Length of postorbital from front to back	112
Horizontal diameter of orbit	57
Nasal horn cores at base:	
Anteroposterior diameter	90
Transverse diameter	41
Height above nasal orifice	127

[1] Lull, R. S., The Ceratopsia: U. S. Geol. Survey Mon. 49, p. 24, footnote, 1907.

THE VERTEBRAL COLUMN.

General features.—The vertebral column of *Brachyceratops* in front of the sacrum is known only from dissociated centra and neural processes, none of which were found in sequential position. Presumably, however, it consists as in *Triceratops* of 22 vertebrae, 8 in the neck and 14 in the thoracic region. The remainder of the vertebral column is known from specimen No. 7953 and comprises the sacrum and a complete articulated series of caudal vertebrae, the first complete tail of a ceratopsian dinosaur to be found. This material is supplemented by articulated portions of two other tails from the same fossil deposit. The vertebral formula may be tentatively given as C 8 ?, D 14 ?, S 6, C 50.

Cervicals.—The cervical region is represented in the collection by a single neural process (see fig. 21), which evidently pertained to one of the posterior cervicals and is complete except for the extremity of the spine. The arch is articulated with the centrum by heavy expanded pedicles. The neural canal is large. The diapophyses, which are heavy and extend outward horizontally from the side of the arch, are high up on the side of and somewhat anterior to the neural process. They are flattened anteroposteriorly but expanded dorsoventrally. The posterior zygapophyses would overhang the end of the centrum. The neural spine rises almost vertically and is much narrower fore and aft than any of the succeeding dorsals.

None of the detached centra can be attributed to the cervical region, for none show a capitular facet on the side for the articulation of the cervical rib. In *Triceratops* it is known from an articulated presacral series that this facet does not change its position on the centrum to the side of the arch until the third dorsal is reached. The process has a greatest transverse diameter of 88 millimeters.

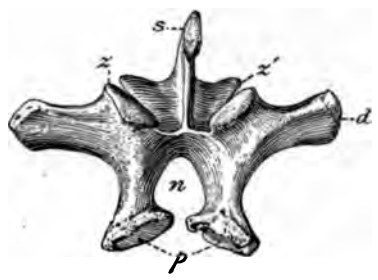

FIGURE 21.—Posterior cervical process of *Brachyceratops montanensis*. No. 7953(?), U. S. N. M. One-half natural size. Viewed from the front. *d*, Diapophysis; *n*, neural canal; *p*, surfaces that articulate with the centrum; *s*, spinous process; *z*, anterior zygapophysis; *z'*, posterior zygapophysis.

Dorsals.—The dorsal region is represented by 12 detached processes and an equal number of centra, from which processes representing the anterior, median, and posterior dorsal regions have been selected for illustration (figs. 22, 23, and 24). The centra shown in the illustrations have been arbitrarily placed, in so far as their relations with the associated dorsal processes are concerned, for none were found articulated. They at least give an idea of the shape and proportions of the centra.

Figure 22 shows front and side views of a vertebra regarded as belonging to the anterior dorsal region. Probably it was the fourth or fifth vertebra, for, as will be observed, the parapophysis on the side of the arch is at the base of the transverse process and is a little removed toward the diapophysis, a condition observed on the fifth dorsal of *Triceratops*. As in *Monoclonius*, *Agathaumas*, and more especially *Triceratops*, the transverse processes incline upward 45° from the horizontal. (See fig. 22.) The transverse processes are long with a beveled articular end for the tuberculum of the rib. The spine is thin transversely, with a backward inclination, its upper extremity only slightly exceeding in height the transverse processes when viewed laterally. The top appears to be without transverse thickening and is somewhat pointed, as in the anterior dorsals of the type specimen of *Triceratops calicornis* Marsh. The centrum provisionally associated with this neural process, when viewed from the front, is seen to have the typical pear-shaped outline of other ceratopsian dorsal centra. The diameter anteroposteriorly appears to be relatively the same as in *Triceratops*, and as in that genus the articular ends are shallowly biconcave. As compared with the cervical process the neural canal is very small. The anterior and posterior zygapophyses are sharply inclined and extend well beyond the center of the vertebra. This vertebra has a greatest transverse width of 100 millimeters; greatest height of 130 millimeters; length of centrum 32 millimeters; height of centrum at center 41 millimeters.

The median dorsal (see fig. 23) shows a higher position of the parapophysis on the inferior side of the transverse process and a broader spinous process with a slight transverse thickening at its upper extremity. The transverse processes are shorter and not so sharply inclined upward

from the horizontal. They are also compressed dorsoventrally and are wider anteroposteriorly than in the more anterior dorsals. The zygapophyses are also not so highly inclined. All these changes are approximated in the *Triceratops* backbone. The greatest transverse width of this vertebra is 99 millimeters; greatest height 132 millimeters; length of centrum 32 millimeters; height of centrum at center 40 millimeters.

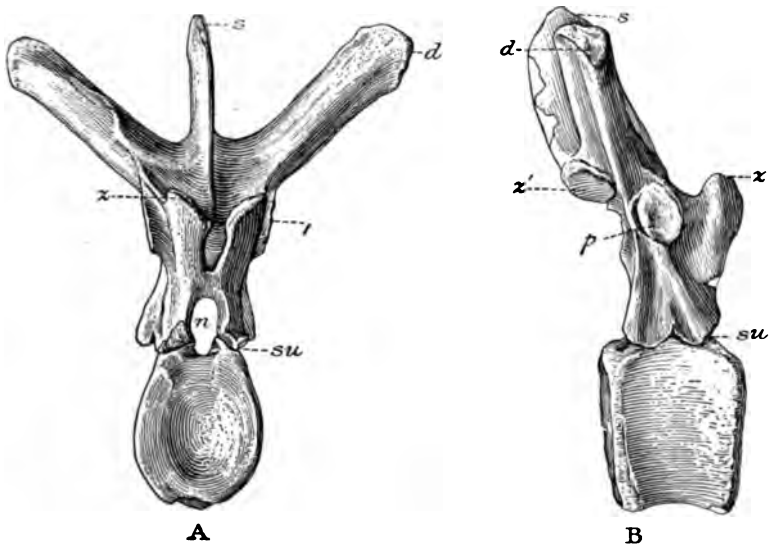

FIGURE 22.—Anterior dorsal vertebra of *Brachyceratops montanensis*. No. 7953(?), U. S. N. M. One-half natural size. A, Front view; B, side view. *d*, Diapophysis; *n*, neural canal; *p*, parapophysis; *s*, spinous process; *su*, suture between centrum and process; *z*, anterior zygapophysis; *z'*, posterior zygapophysis.

The position in the vertebral column of the posterior dorsal (see fig. 24) may at once be recognized by the horizontal plane of the anterior and posterior zygapophyses, by the broader and shorter spine, and by the shorter, weaker, and more depressed transverse process. Moreover, the parapophysis is well out on the lower side of the transverse process toward the diapophysial articular surface for the rib. The incisions for the prezygapophyses and postzygapophyses are much deeper than in the preceding dorsals. The greatest transverse width of this vertebra is 95 millimeters; greatest height 100 millimeters; greatest length of centrum 32 millimeters; greatest height of centrum at center 35 millimeters.

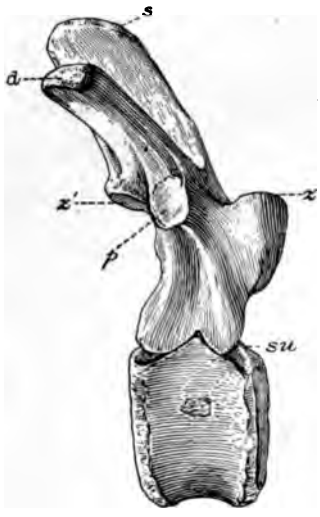

FIGURE 23.

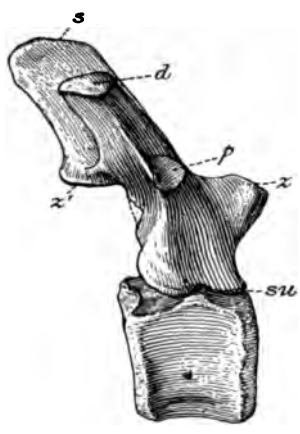

FIGURE 24.

The sutural surfaces of the centra (see fig. 25) nearly all agree in having two lateral pits separated by a short median transverse ridge.

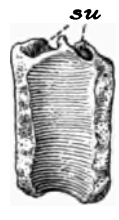

FIGURE 25.

FIGURE 23.—Median dorsal vertebra of *Brachyceratops montanensis*. No. 7953(?), U. S. N. M. One-half natural size. Lateral view. *d*, Diapophysis; *p*, parapophysis; *s*, spinous process; *su*, suture between centrum and process; *z*, anterior zygapophysis; *z'*, posterior zygapophysis.

FIGURE 24.—Posterior dorsal vertebra of *Brachyceratops montanensis*. No. 7953(?), U. S. N. M. One-half natural size. Lateral view. *d*, Diapophysis; *p*, parapophysis; *s*, spinous process; *su*, suture between centrum and process; *z*, anterior zygapophysis; *z'*, posterior zygapophysis.

FIGURE 25.—Centrum of dorsal vertebra of *Brachyceratops montanensis*. No. 7953(?), U. S. N. M. One-half natural size. Lateral view. *su*, Suture for the spinous process.

The last or sacrodorsal is represented only by the centrum in No. 7953. Though found detached from the first sacral of that specimen, it was in close association with it in the matrix and in an adult individual would undoubtedly have been firmly coossified with the sacral as indicated by the sutural surface of its posterior end. The centrum is slightly longer and more massive than any of the centra attributed to the dorsal region. A measurement taken at the

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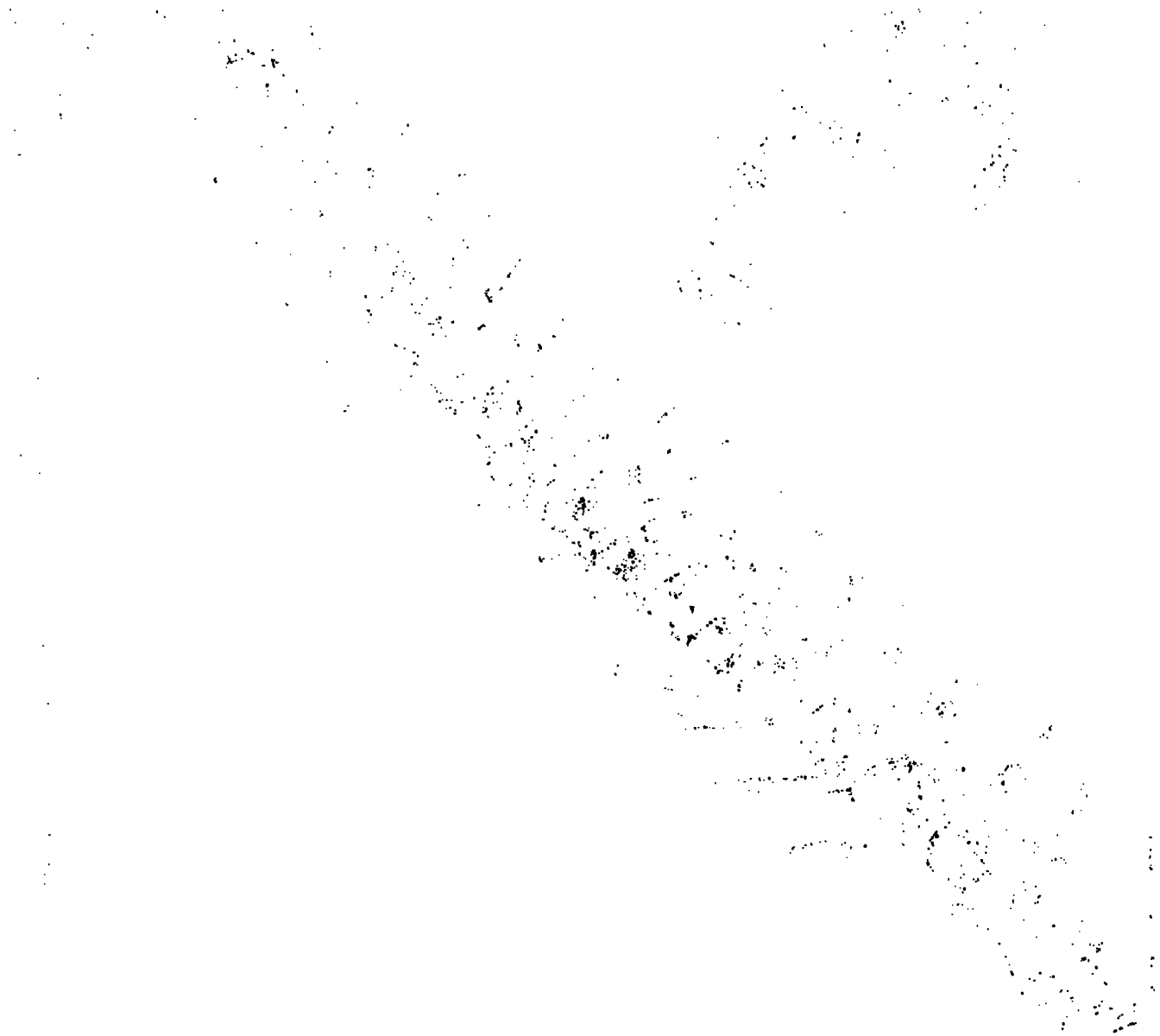


end shows it to be wider than high. The lateral surfaces are flattened in a vertical direction, and the ventral surfaces are broadly flattened with two shallow longitudinal grooves. A heavy articular facet on the posterior external angle contributes to the support of the first sacral rib. The greatest length of centrum is 35 millimeters; and the greatest height, taken at the center, is 31 millimeters.

Sacrum.—The sacrum in the paratype, No. 7953, is represented by all the centra, portions of the neural processes of the posterior vertebrae, and numerous detached sacral ribs. (See Pl. III, *B*, *C;* text fig. 26.) These parts have been compressed, but taken all in all give a fairly

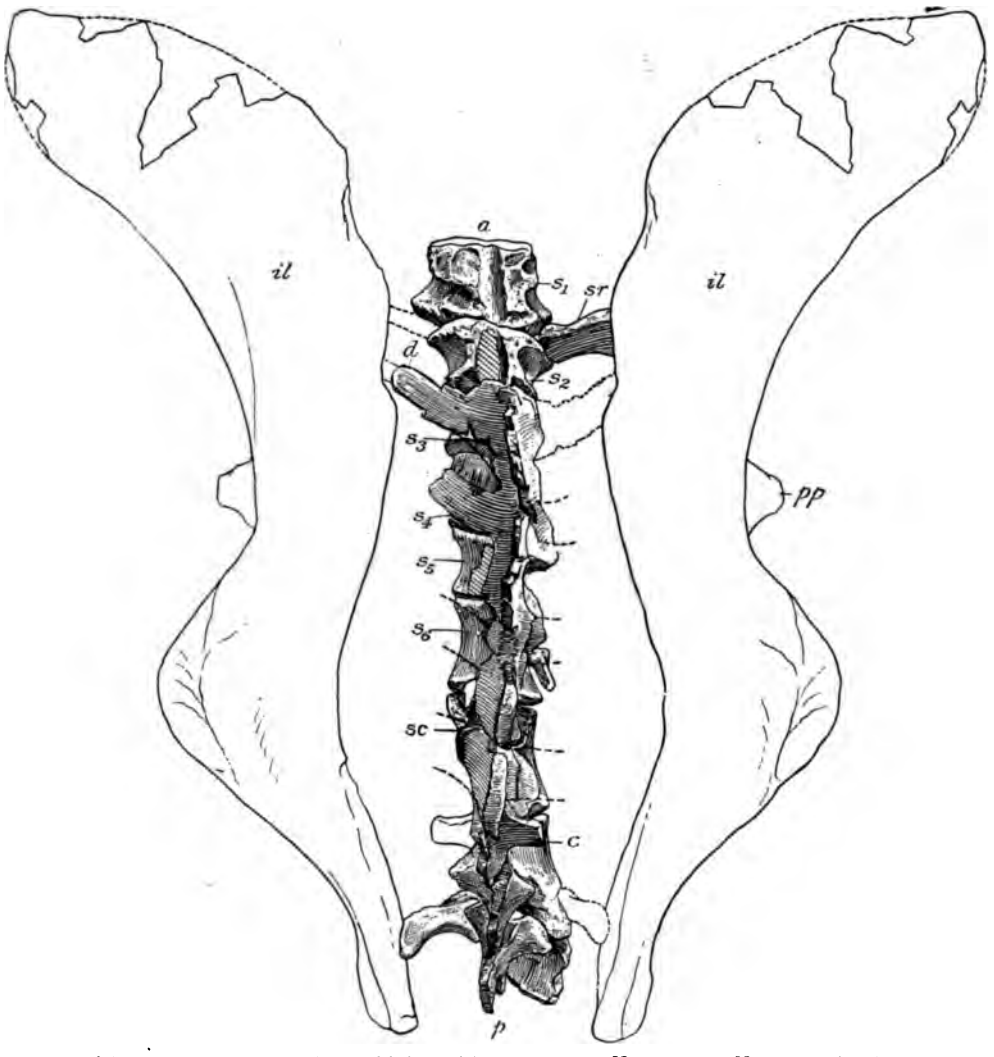


FIGURE 26.—Sacrum of *Brachyceratops montanensis* with ilia in position. Paratype. No. 7953, U. S. N. M. One-fourth natural size. Superior view. *a*, Anterior end; *d*, diapophysis; *il*, ilium; *p*, posterior end; *pp*, pubic peduncle; s_1, s_2, s_3, s_4, s_5, s_6, sacral vertebrae Nos. 1 to 6; *sc*, sacrocaudals; *sr*, sacral ribs.

good idea of the chief characteristics of the sacrum in *Brachyceratops*. The centra are all suturally united and in an adult individual would doubtless be firmly coossified, as in other ceratopsians. The paratype has nine articulated centra, of which the anterior six are regarded as true sacrals and the posterior two as true caudals. The remaining intermediate vertebra between tail and sacrum constitutes a modified caudal that functions to a certain extent as a sacral and can therefore be designated a sacrocaudal (*sc*, fig. 26).

The sacrum of the paratype, including the sacrodorsal and the sacrocaudal, had eight centra with sutured articular ends. whereas *Monoclonius* and *Triceratops* had ten such vertebrae.

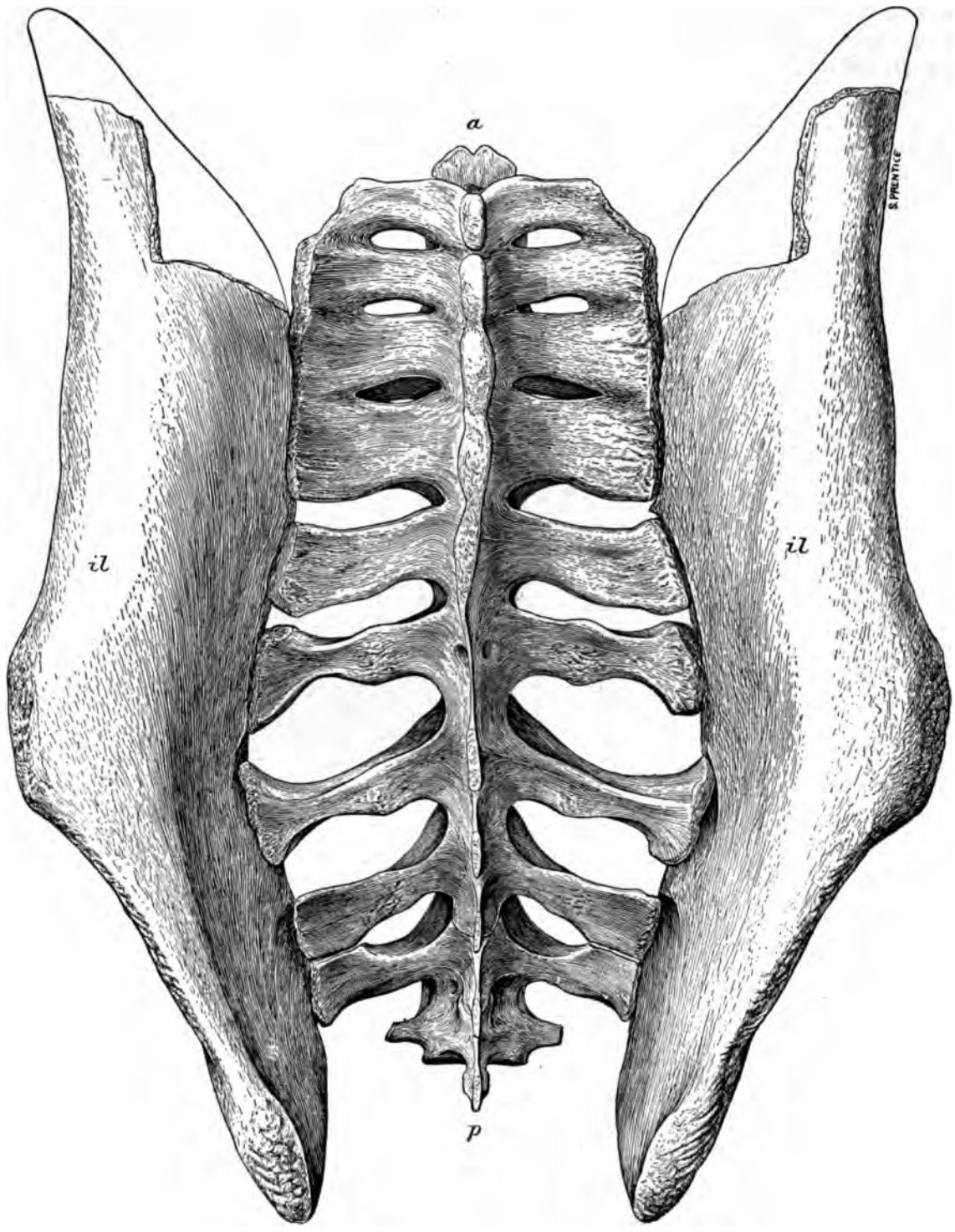


FIGURE 27.—Sacrum of *Triceratops prorsus* Marsh with ilia in position. No. 4842, U. S. N. M. One-twelfth natural size. Superior view *a*, Anterior end; *il*, ilium; *p*, posterior end. (After Hatcher.)

This, however, may not constitute a constant difference between these genera, for it is quite possible that in some specimens of *Brachyceratops* one or more caudals have acquired such an articulation, thus bringing the total number up to 10, as in known ceratopsian sacra.

The first sacral may be recognized at once by the great transverse breadth of the centrum, its flattened ventral surface, and the inferior position of the posterior articular facets for the second sacral rib (s_1, Pl. III, *C*). The second sacral centrum is also distinguished from all others by the much greater breadth of the anterior as compared with the posterior extremity. The centra of the remaining sacrals are of about equal dimensions, higher than wide, constricted medially, with slightly flattened inferior surfaces.

A second specimen (No. 8072, U. S. N. M.), however, shows centra that are broader than high and that have a shallow longitudinal depression on their inferior surfaces. The differences are in all probability due to crushing. The first three vertebrae of the sacral region, which include the sacrodorsal, are decidedly heavier than any that succeed them. The sacral ribs are borne jointly by all the centra. The first rib joins the centra by well-developed facets on the superior, posterior, external angle of the dorsosacral and on the superior, anterior, external angle of the first sacral. The second and strongest sacral rib of the series articulates jointly with the first and second dorsals low down on the sides of the centra, the inferior surface of the rib being on a level with the ventral surface of the sacrals. (See Pl. III, *C*.) The succeeding ribs articulate with facets that are but little below the level of the floor of the neural canal.

Longitudinally the sacrum is strongly arched (see Pl. III, *B*), though in all probability this arching has been much exaggerated in this specimen by post-mortem causes.

The few spinous processes are exceedingly short thin plates of bone with little transverse thickening of their superior extremities. That these were united into a bony plate is indicated by a detached sacral process belonging to another individual (No. 8072, U. S. N. M.), which shows sutural edges fore and aft that continue to the top of the spine. The same condition prevails on the spine of the fifth sacral (see Pl. III, *B*), so it would appear that this plate may have been continuous from the first to the fifth, much as it is in *Triceratops*. The relative shortness of the spines in *Brachyceratops* would at once distinguish its sacrum from that of the former genus.

As in *Triceratops* the spinal cord appears to have been only slightly enlarged in the anterior sacral region. The diapophyses are comparatively weak and are given off on a horizontal plane from the neural arches, with thin ends directed forward. (See fig. 26.) Their inferior borders extend obliquely downward and inward and present a narrow sutural edge for articulation with the upper and inner borders of the sacral ribs, which they overlap superiorly. Nearly all the transverse processes are missing, but their point of origin, as shown by the broken surfaces, is indicated in figure 26 by parallel dotted lines.

Though many sacral ribs were found none were articulated and a description of them would add little to the positive knowledge of the structure of the sacrum.

Measurements, in millimeters, of centra of sacral vertebrae.

	I	II	III	IV	V	VI
Greatest length	36	35	32	29	30	30
Greatest transverse diameter:						
Anterior end	39	47	.....	25	24	28
Posterior end	58	33	32	23	28	28

Caudal vertebrae.—For the first time since the discovery of ceratopsian dinosaurs a complete caudal series of 50 vertebrae (paratype No. 7953) is available for study.

The greater number were found articulated, and such displacement as existed was so slight that there can be no question that they represent a consecutive series. Forty-six of them are represented in Plate III, *A*, the remaining four being attached by the matrix to the sacrum. (See Pl. IV.)

The centrum of the first or sacrocaudal (*sc*, Pl. III, *C*) is longer than wide and has an articular facet on its superoantero lateral angle for the articulation of the last sacral rib. The neural arch, although poorly preserved, indicates that the spine was distinct from the spines forward of it. It had a decidedly backward inclination. The anterior and posterior zygapophyses are also differentiated, not coalesced, as in all preceding sacral vertebrae. The diapophyses on the first and second caudals are given off from the sides of the arch well below the zygapophyses but above the neurocentral suture, but that on the fourth caudal is below that suture. The centrum of the third caudal is so badly crushed that it gives a poor idea of its proportions. The arch, however, shows the spine to be narrower, anteroposteriorly, than it is in the first and second caudals, and the diapophysis is somewhat lower on the side of the arch than it is in the first caudal.

The third and fourth caudals are represented by the centra only, which, like all that follow, are short and have slightly biconcave ends and a transverse width that usually exceeds both the longitudinal and the vertical diameters.

Transverse processes are present on the first 25 vertebrae. The anterior ones, except possibly the first two or three, are long and flattened and have heavy expanded articular ends that unite about equally with the centrum and the pedicles of the arch. (See fig. 28.) These

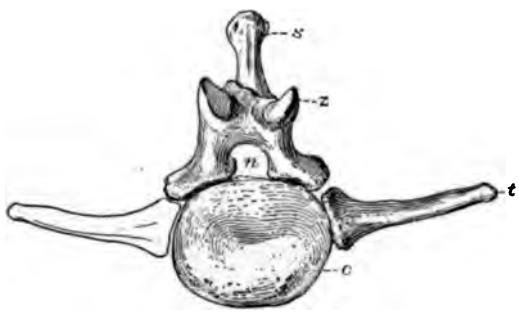


FIGURE 28.

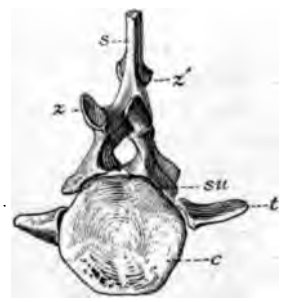


FIGURE 29.

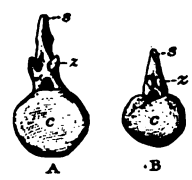


FIGURE 30.

FIGURE 28.—Anterior caudal vertebra (eighth) of *Brachyceratops montanensis*. Paratype. No. 7953, U. S. N. M. One-half natural size. Front view. *c*, Centrum; *n*, neural canal; *s*, spine; *t*, transverse process; *z*, anterior zygapophysis.

FIGURE 29.—Median caudal vertebra of *Brachyceratops montanensis*. Paratype. No. 7953, U. S. N. M. One-half natural size. Front view. *c*, Centrum; *s*, neural spine; *su*, neurocentral suture; *t*, transverse process; *z*, anterior zygapophysis; *z'*, posterior zygapophysis.

FIGURE 30.—Distal caudal vertebrae of *Brachyceratops montanensis*. Paratype. No. 7953, U. S. N. M. One-half natural size. Front view. A, Twenty-third; B, twenty-sixth. *c*, Centrum; *s*, spine; *z*, anterior zygapophysis.

gradually shorten posteriorly. In the twentieth centrum the transverse is united entirely with the centrum and all trace of sutural articulation is obliterated, though in the nineteenth it is visible and slightly in contact with the pedicle of the arch.

The neural arches throughout the caudal region are low. The short compressed spines of the anterior caudals with transversely expanded upper extremities (see Pl. III, *A*) gradually narrow and become smaller and in the midcaudal region show no thickening of their upper ends. (See fig. 29.)

The anterior zygapophyses are finger-like and extend forward with articular faces that face upward and inward. (See fig. 28.) The posterior zygapophyses are well up on the posterior border of the spine and overhang the ends of the centra. Functional zygapophyses persist down onto the distal fourth of the tail. In the distal caudals (fig. 30) the neural processes are present on the second to the last, but are without spines; also the processes, instead of occupying the middle of the centrum, have shifted their position forward toward the anterior end, as in *Stegosaurus*. These most distal caudals also have convex distal extremities and concave proximal articular ends and are without chevron facets. The anterior caudals as far back as the thirty-ninth caudal from the sacrum have oblique chevron facets on the posterior ends of the centra and may have had them nearly to the tip of the tail, as in *Stegosaurus*. The tip of the tail is composed of three coossified centra, the final one being hardly more than a short, rounded obtusely pointed ossicle.

THE RIBS.

Brachyceratops, like other members of the Ceratopsia, doubtless had cer none of them have been preserved. A considerable number of thoracic ribs, been found and serve to illustrate the various modifications in the dorsal region. All are double headed. The more anterior dorsal ribs are distinguished by the their shafts and the elevation of the tuberculum above the capitular process, wh

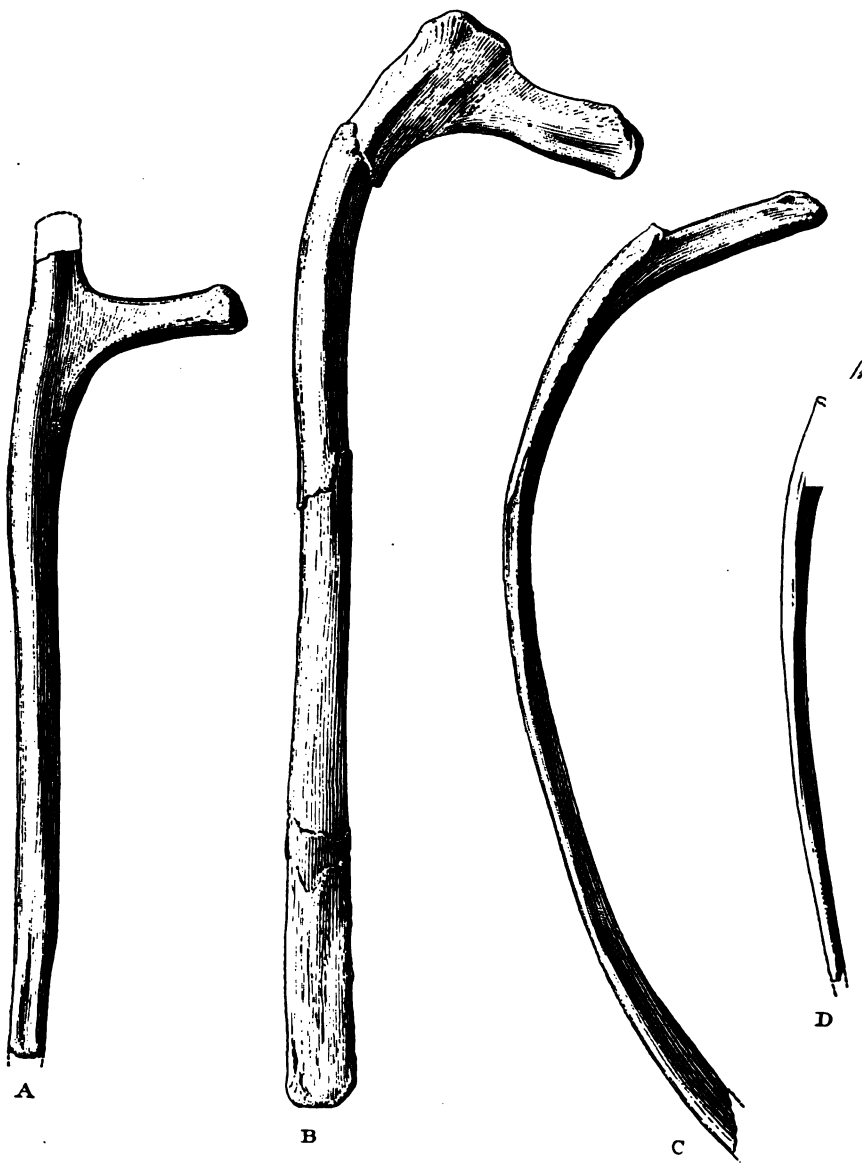


FIGURE 31.—Dorsal ribs of *Brachyceratops montanensis*. No. 7953(?), U. S. N. M. A, Second dorsal rib from the right s rib; C, median dorsal rib; D, posterior dorsal rib. All one-half natural size.

at nearly right angles to the shaft, which is subcylindrical in cross section. A of what is regarded as a second dorsal rib from the right side is shown in figur succeeded by the type shown in figure 31, B. These two are the longest of the s more arched upper extremity which throws the capitular process downward a right angle to the longer axis of the shaft, thus forming a flattened lank body c in *Stegosaurus* and *Diplodocus*. The shaft of these ribs is flattened, of fairly u and has a truncated distal extremity that shows no thickening. The median ribs

are more curved from end to end, with an upward inclination of the capitular process and a reduced tubercular facet. The posterior ribs (see fig. 31, D) are slenderer and straighter, with a capitular process but little angulated in relation to the shaft. The capitulum and tuberculum are not so far removed from one another as in more anterior ribs, this being due to the shifting of the facets on the dorsal vertebrae. In figure 32 is shown a small curved bone that is doubtfully regarded as representing the last dorsal rib. It has a single cupped articular face (*a*, fig. 32) on its proximal extremity, and if correctly identified it probably curved down from the diapophysis on the inside of the ilium, with which it was doubtless in contact, as in *Stegosaurus*, *Thescelosaurus*, and presumably many other dinosaurs.

THE CHEVRONS.

No. 7953 includes chevrons from the anterior, middle, and posterior parts of the tail. In the anterior portion they are longer than the spines of the vertebrae with which they articulate, but posteriorly they appear to reduce more rapidly than the spinous processes. Throughout the series they have the usual Y shape, though a few of the anterior ones have the articular ends in contact on the median line, thus bridging the cleft between the branches. More posteriorly, however, all have these ends separate.

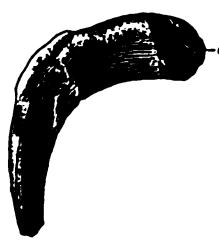


FIGURE 32.

FIGURE 33.

FIGURE 32.—Posterior dorsal rib of *Brachyceratops montanensis*. No. 7953(?), U. S. N. M. One-half natural size. Posterior view. *a*, Articulating face.

FIGURE 33.—Chevron of *Brachyceratops montanensis*. Paratype. No. 7953, U. S. N. M. Three-fourths natural size. *a*, Articulating face.

The great length of the upper branches as compared with the extremely short ones of the distal portion serves to distinguish the chevrons of *Brachyceratops* from those of other described dinosaurs. The articulating facets are confined to the posterior face, though they look somewhat upward in the anterior caudal region, but in the median and distal portions of the tail they are more on the proximal face. The free end is bluntly truncated throughout the series. The shaft is rounded in the anterior members and is somewhat flattened transversely in the median and posterior chevrons. All are unusually straight and none have expanded free ends. An anterior chevron measures 44 millimeters in length.

A number of small bones found in the matrix surrounding the anterior portion of the tail of No. 7953 have a flattened, rounded articular facet very similar to those of the anterior chevrons, the opposite end being slightly expanded in the same plane. (See fig. 33.) The shaft is also greatly curved from end to end. It was at first thought these might be caudal ribs, but the absence of articular ends on the transverse processes (the true caudal ribs in this specimen) does not adapt itself to this explanation, and the only alternative that suggests itself is that they are chevron bones, the two branches being separate at their free extremities. Such a condition is unknown in any reptile living or extinct, and it is quite probable that this explanation is incorrect.

OSSIFIED TENDONS.

Ossified tendons (*t*, Pl. III, *B*) were found attached by matrix along both sides of the neural spines of the sacrum in the paratype No. 7953. That these ossifications were also present on the anterior portions of the tail is indicated by a few fragments still attached to the vertebrae by matrix. Numerous fragments of these tendons were found in the soft matrix immediately surrounding the tail, and doubtless they also extended forward along the dorsal region, as in *Triceratops*. They are slender, rounded, rodlike ossifications, averaging about 2 millimeters in diameter.

THE SHOULDER GIRDLE AND FORE LIMB.

Scapula.—The complete scapula of *Brachyceratops* is as yet unknown, but fragmentary portions of two bones of paratype No. 7958 supplement one another sufficiently to give a very accurate conception of its general shape and proportions. (See fig. 34.)

The scapula is long and narrow and is somewhat bent longitudinally to better conform to the curve of the thoracic cavity. The articular end is heavy and has a cupped surface (*g*, fig.

34) for the articulation of the humerus. The thinner upper portion of this end is missing. The vertical breadth of the shaft decreases to its mid length and again gradually expands to the squarely cut-off upper extremity. The lower border on the proximal half is broadly rounded

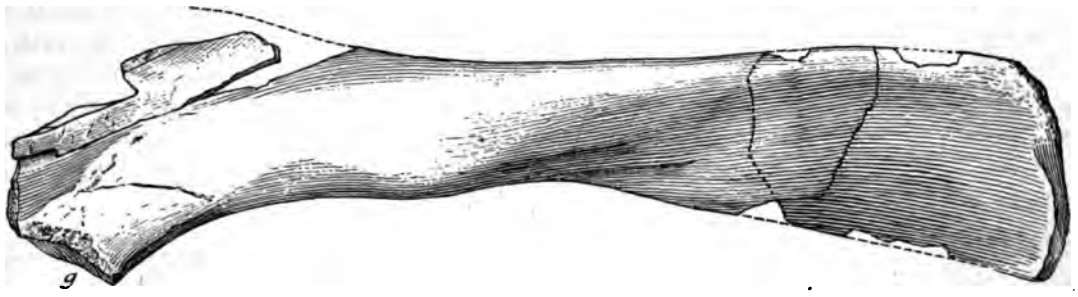


FIGURE 34.—Left scapula of *Brachyceratops montanensis*. No. 7958, U. S. N. M. One-half natural size. External view. *g*, Glenoid cavity. The drawing is a composite made from two bones, their overlap being indicated by the dotted line.

but gradually thins toward the upper end to a sharp edge. The upper end is without transverse thickening. A heavy rounded ridge extends upward on the outer surface diagonally from the posterior border of the glenoid cavity to the upper anterior border, whence it continues backward as a thickening of this margin. In general proportions and outline the scapula of *Brachyceratops*, although less than half the size, very closely resembles the scapula of *Monoclonius dawsoni* as described and figured by Lambe.[1] It is to be distinguished from the scapula of *Triceratops* as figured by Hatcher [2] by its lack of an upward expansion of the anterior upper border of the blade and by the less prominent development and more diagonal direction of the ridge on the external surface.

At present the coracoid and humerus are unknown.

Ulna.—The ulna is, of course, very much smaller than in *Triceratops* but is otherwise similar, being heavy above and but little expanded on the distal end. The olecranon process is massive and is produced far above the main articulating surface for the humerus. The shaft is much flattened anteroposteriorly, its posterior side being shallowly concave transversely throughout the greater part of its length. The anterior face of the distal portion is broadly rounded transversely but, more proximally, changes to a decided concave surface for the reception of the rounded head of the radius. The distal articular end is smooth and extends considerably upward on the posterior side and is not visible from the front. (See fig. 35.)

The outline of the olecranon was drawn from a second specimen, and its shape is correct. The greatest length of the left ulna (see fig. 35) is estimated at about 213 millimeters.

Radius.—The radius is more slender than the ulna and has expanded ends, of which the distal is the heavier. The proximal end is angularly rounded and has a shallow cupped articular surface. The shaft in cross section near its middle is oval. The distal end is expanded transversely but is somewhat compressed anteroposteriorly. A complete radius is not known, but proximal and distal portions of it are shown in figure 36.

Fore foot.—Nothing is known of the structure of the carpus and but little of the metacarpus. Figure 37 shows all the bones in the collection from Montana that are regarded as pertaining to the fore foot of *Brachyceratops*.

FIGURE 35.—Left ulna of *Brachyceratops montanensis*. No. 8076, U. S. N. M. One-half natural size. Anterior view. *o*, Olecranon process; *r*, concavity for proximal end of radius. Olecranon restored from the ulna of a second individual.

[1] Lambe, L. M., On Vertebrata of the mid-Cretaceous of the Northwest Territory: Contr. Canadian Paleontology, vol. 3, pt. 2, p. 60, pl. 19, fig. 4, 1902.

[2] Hatcher, J. B., The Ceratopsia: U. S. Geol. Survey Mon. 49, p. 78, fig. 84, 1907.

The metacarpus is represented by one fragmentary and two complete metacarpals (*a*, *b*, *c*, fig. 37), but nothing is positively known of the positions they occupied in the foot.[1] The phalanges (*d*, *e*, *f*, *g*, *h*, fig. 37) are depressed rectangular elements. It was on account of their thin depressed nature that they were assigned to the manus, for otherwise they appear indistinguishable from the phalanges of the pes. Similarly, the ungual phalanx (*i*, fig. 37) is assigned to the fore foot, being elongated and more sharply pointed than the shorter, more broadly rounded unguals associated with the partly articulated hind feet. (See figs. 46, 47, pp. 34, 35.)

FIGURE 36.—Proximal and distal portions of the radius of *Brachyceratops montanensis*. Nos. 8077 and 8078, U. S. N. M. One-half natural size. A, Proximal portion; B, distal portion.

THE PELVIC GIRDLE AND HIND LIMB.

Ilium.—The ilium is an elongate, irregularly shaped bone, consisting of a comparatively thin, horizontal, expanded anterior part and a nearly vertical but narrower posterior part. (See figs. 38 and 39.) The inner and outer borders of the dorsal face (see fig. 26, p. 21) each describe a sigmoid curve. The transversely expanded anterior plate of the ilium has a convex dorsal and a concave ventral surface. The external border is not continuous from end to end, as in the ilium of *Triceratops* and *Monoclonius* (compare figs. 39 and 40), but extends backward and downward from the anterior portion and fades out on the external side above the pubic peduncle. Above and somewhat forward of this termination a second rounded border arises from the outer side of the convex superior surface of the anterior plate of the ilium and continues posteriorly, completing the outer border of the middle section and the upper border of the posterior portion.

In contrast with the ilia of *Monoclonius*, *Agathaumas*, and *Triceratops* (compare figs. 39 and 40), the ilium of *Brachyceratops* is not only much smaller, but the transverse expansion of its anterior plate, its greater inclination outward, and the differentiation of the thickened deflected border above the ischiac peduncle all distinguish it from the other described forms. In the development of this heavy deflected process above the ischiac articulation and in being longer than the femur it somewhat resembles the *Stegosaurus* ilium. (Compare figs. 26 and 27, pp. 21 and 22.)

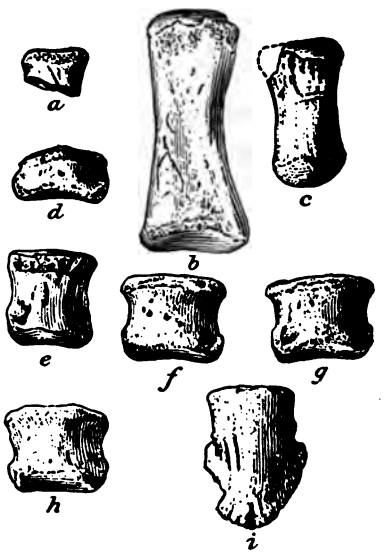


FIGURE 37.—Bones provisionally identified as pertaining to the fore foot of *Brachyceratops montanensis*. No. 8079, U. S. N. M. Superior view. *a*, *b*, *c*, Metacarpals; *d*, *e*, *f*, *g*, *h*, phalanges; *i*, ungual phalanx.

Near the middle the internal border is greatly thickened dorsoventrally and is produced downward to form the superior border of the acetabulum and the pubic and ischiac peduncles. The anterior peduncle is rather slender, but the posterior one is exceedingly heavy in all dimensions, as shown in figures 38 and 39. The posterior plate, when the ilium is in a vertical position, has its superior border inclined slightly outward from the perpendicular. In *Brachyceratops* this upper border is relatively thin, its posterior end is cut off obliquely and its inferior border is concave from end to end; whereas in *Triceratops* it is much thickened, its posterior end is bluntly rounded, and its inferior border is slightly convex from end to end. On the internal side the usual cupped articulating surfaces for the diapophyses and sacral and caudal ribs appear.

[1] For convenience in reference these foot bones are catalogued under one number. This does not imply that they belonged to one individual, for they were found among the scattered surface fragments.

The measurements of the left ilium of paratype No. 7953 are as follows:

Greatest length of ilium	
Greatest width of anterior blade	
Greatest width at center, transversely	
Greatest depth of posterior blade	
Greatest depth at center of acetabulum	
Greatest width across deflected external process	

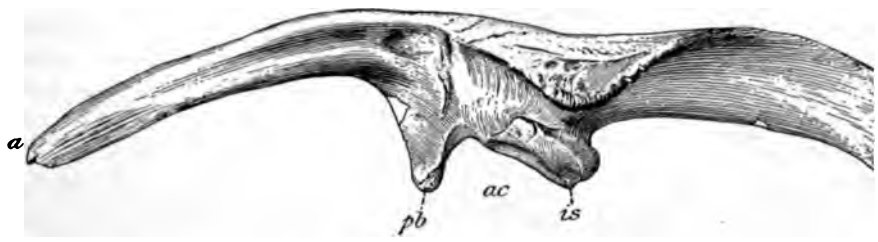


FIGURE 38.—Left ilium of *Brachyceratops montanensis*. No. 7953, U. S. N. M. One-third natural size. External vie
ac, acetabulum; *is*, ischiac peduncle; *p*, posterior end; *pb*, pubic peduncle.

Pubis.—The pubis in *Brachyceratops* consists of an elongated, transversely f
of bone, a prepubic portion, and a short, slender, curved, somewhat rudimen
postpubis. The anterior portion is expanded dorsoventrally into a broadly rou
is little thickened transversely. The rugose articulating surface for the peduncl
is relatively not so heavy as in *Triceratops*, but the broad posteriorly directed p
the internal wall of the acetabulum is as well developed as in that genus and
the same extent to the formation of the inner boundary of the acetabulum. I

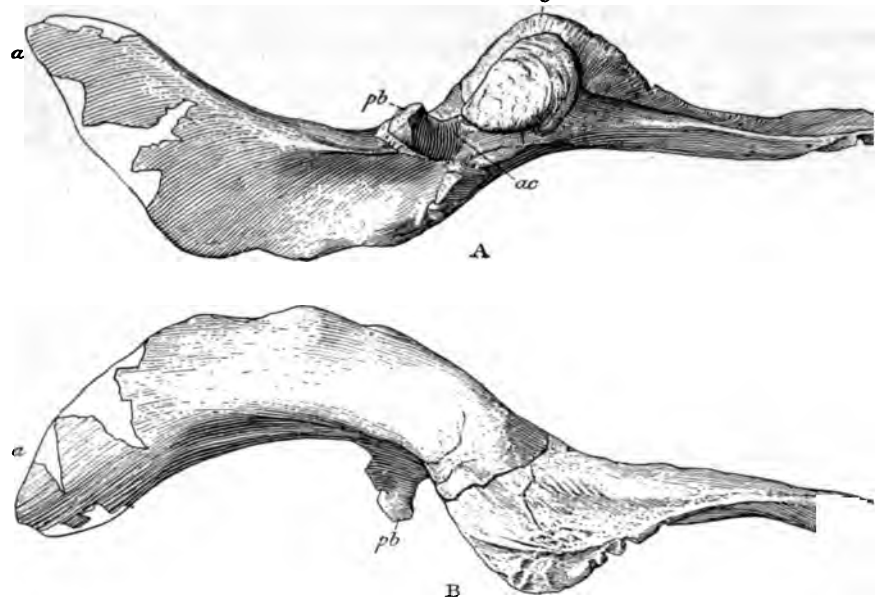


FIGURE 39.—Left ilium of *Brachyceratops montanensis*. No. 7953, U. S. N. M. One-third natural size. A, Ventral vi
view. *a*, Anterior end; *ac*, acetabulum; *e*, overhanging crest; *p*, posterior end; *pb*, pubic peduncle.

pubes before me is the postpubis entire, all specimens lacking portions of the
their extension posteriorly appears to be about the same as in *Triceratops*. Ther
pubic foramen, but an elongated cleft between the postpubis and the flattened
of the prepubis probably functioned as such. The greatest length of the left
7953 is 192 millimeters. The chief characteristics of this bone are well shown ir

Ischium.—In the collection from Montana there are portions of no less th
of *Brachyceratops*, but only one of them is complete. (See fig. 42.) It is a long,
bone with an expanded proximal extremity, carrying a heavy articulation for the is

of the ilium and sending forward and upward a process which articulates at its extremity with the pubis. The articulated ischia curve toward the median line and were probably united by cartilage for a short space near their distal extremities. The shaft is subcircular throughout the median part of its length but becomes somewhat triangular toward its reduced distal end. The right ischium, shown in figure 42 (No. 8073, U. S. N. M.), has a greatest length of 340 millimeters.

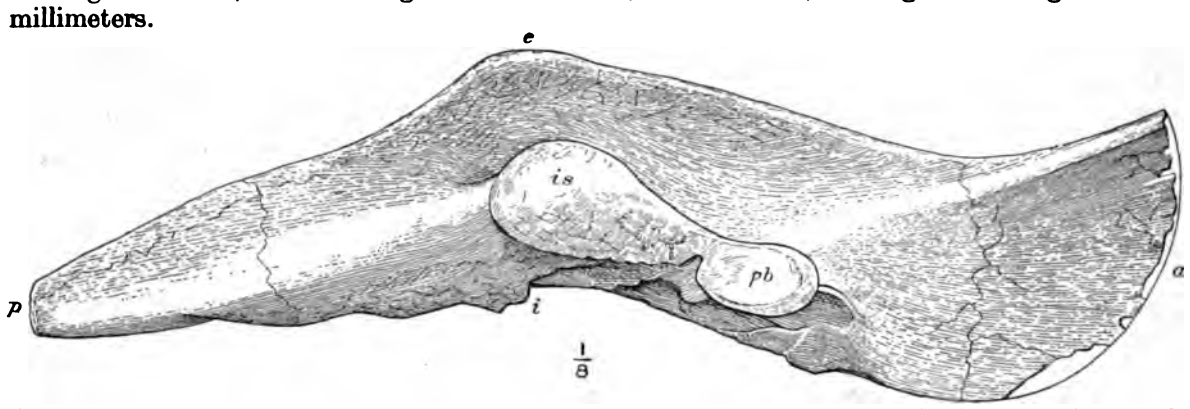


FIGURE 40.—Right ilium of *Triceratops flabellatus* Marsh. No. 1821, Yale Museum. One-eighth natural size. Inferior view. *a*, Anterior end; *e*, external border; *i*, internal border; *is*, ischiac peduncle; *p*, posterior end; *pb*, pubic peduncle. (After Hatcher.)

Femur.— The femur is represented in the collection by one complete bone and good-sized portions of four others. All are the same size and differ only in minor details, which may be entirely attributed to post-mortem causes.

In *Brachyceratops* the femur is slightly more than one-fourth as long again as the tibia and in *Triceratops* it is half as long again. In other words, in *Brachyceratops* the ratio of length of the tibia to the femur is 1 to 1.28, and in *Triceratops* it is 1 to 1.59. Proximally the head is differentiated from the shaft and the greater trochanter by a short neck that is less well defined than that found in the femur of *Triceratops* and that much more closely resembles the same bone in *Monoclonius crassus* Cope. Viewed from above the head is subglobular in outline, with a rounded notch or groove on the external posterior border. The great trochanter (*b*, fig. 43) is expanded anteroposteriorly. On the anterior external angle and separated from the great trochanter by a deep cleft is a flattened finger-like lesser trochanter (*a*, fig. 43), which rises nearly to the height of the greater trochanter. This process is also present in *Triceratops* but is shorter and broader and is about equally prominent externally and anteriorly, whereas in *Brachyceratops* it is more prominent externally. Though doubtless preserved in *Monoclonius* this process is not shown in the figures of that bone by Hatcher.

FIGURE 41.—Left pubis of *Brachyceratops montanensis*. No. 7953, U. S. N. M. One-half natural size. Internal view. *a*, Anterior end; *b*, posterior end; *c*, articulating surface for pubic peduncle; *p*, prepubic portion; *p'*, postpubic portion.

An elongated fourth trochanter rests wholly on the proximal half of the posterointernal border of the shaft. In *Triceratops* the center of this trochanter is about midway between the proximal and distal ends. The condyles of the distal end are heavy, the internal being larger than the external. The intercondylar notch is deep and narrow, and the anterior intercondylar groove is wide and concavely rounded transversely and extends well up on the anterior face of the bone. The principal characters of the femur are well shown in figure 43. The measurements of specimen No. 7953 are as follows:

	Millimeters.
Greatest length	337
Greatest breadth:	
Proximal end	100
Distal end	83
Least breadth of shaft	45

Tibia.—The tibia is relatively short and is constricted medially but has exp
The greatest proximal expansion is anteroposterior (see fig. 44), and the greatest dis
ment is transverse. The proximal surface is rugosely roughened. This end show
into two backward projecting condyles, about subequal in size and separated by a n
condylar notch of moderate depth. The enemial crest is heavy and projects well forward of the median part of the shaft.

The distal end is divided into two surfaces, an inner with a beveled distal surface that articulates with the astragalus and constitutes more than one-half of the transverse diameter of this end, and an outer that extends distally to the level of the inferior border of the articulated astragalus and closely embraces that element on the external side. The anterior side of this part of the tibia is flattened for the articulation of the fibula. The measurements of tibia No. 7957 are as follows:

	Millimeters.
Greatest length	268
Greatest diameter:	
Proximal end:	
Anteroposteriorly, estimated	99
Transversely	41
Distal end:	
Anteroposteriorly	30
Transversely	71

Fibula.—The fibula is shorter than the tibia. It is slender and has expanded extremities, and its shaft is flattened in the proximal half but subcylindrical below. The bone is bowed longitudinally, and the ends are angulated to one another, that is, planes passed through their longer diameter if produced would cut one another at 45°.

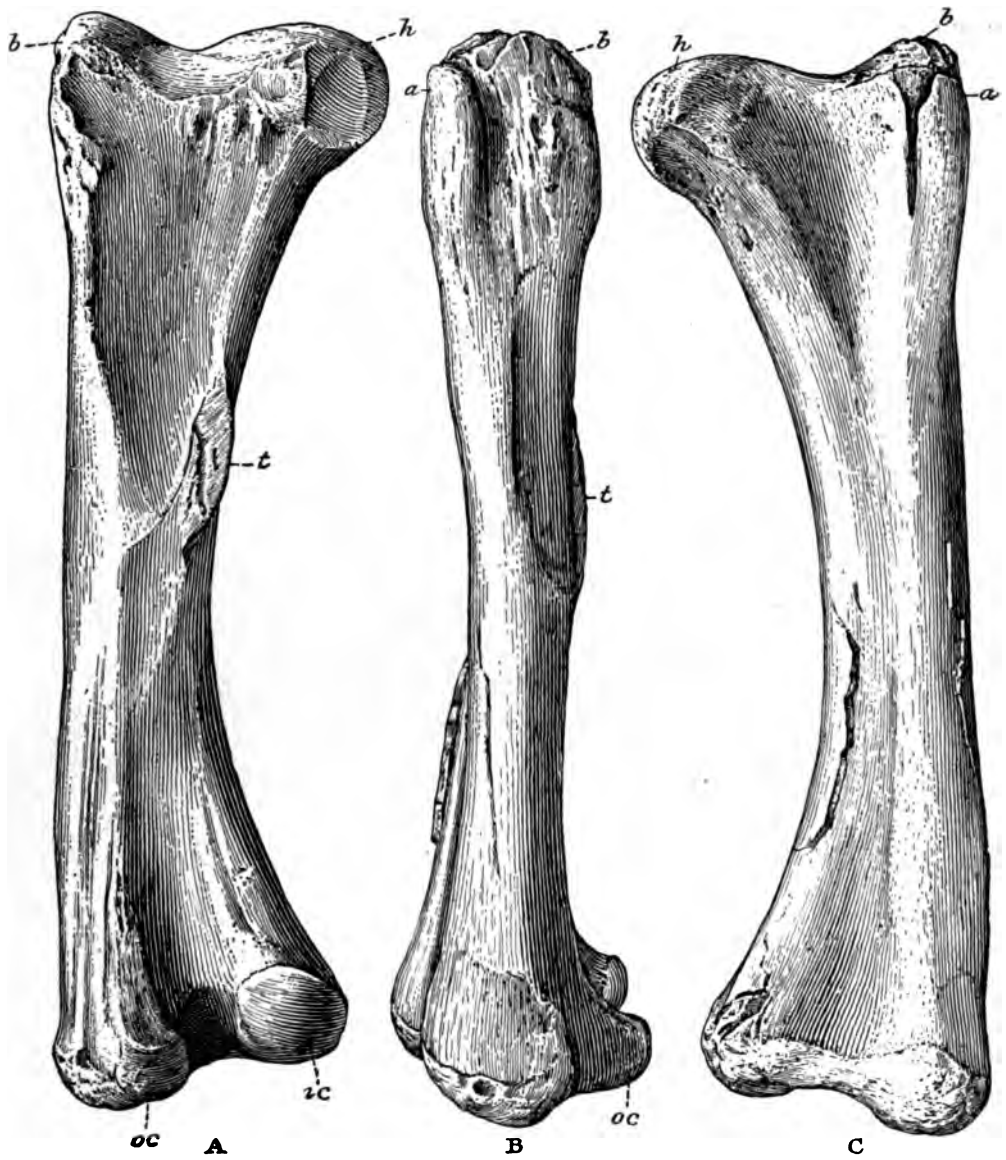
At the proximal end the face toward the tibia is slightly concave and that away from the tibia is convex anteroposteriorly. The lower articular face is flattened and was closely applied to the anterior flattened face of the tibia. The distal articular end is shallowly cupped and triangular in outline, its widest portion being internal, with a knoblike projecting facet for the calcaneum as in *Camptosaurus*. A side view of the fibula is shown in figure 45. The greatest length of the fibula of paratype No. 7957 is 246 millimeters, and the greatest width of the distal end is 34 millimeters.

FIGURE 42.—Right ischium of *B*
tanensis. No. 8073, U. S. N. M.
size. External view. *il*, Proc
with ilium; *p*, process that arti

THE HIND FOOT.

The specimens.—Notwithstanding the great number of ceratopsian remains collected in the Rocky Mountain region since 1855, the present specimens are the first to be described that give an adequate conception of the complete skeletal structure of the pes in the horned Dinosauria. They are of additional interest because they pertain to one of the earliest known members of the ceratopsian group of dinosaurs and will be of especial val
mining the structural changes that have taken place in the hind feet of the late
highly specialized ceratopsians of the Lance when these are found.

Except the vestigial digit V, the complete hind foot of *Brachyceratops* is shown in figure 46 elements drawn in outline have been introduced from the evidence of the partly articu- l foot No. 7956 (see fig. 47), in which the phalanges of digit I were present but were turned ı beneath the other metatarsals. The fourth phalanx of digit IV is also present in that and is articulated with the third, which agrees perfectly with the third phalanx of foot 7957.



E 43.—Femur of *Brachyceratops montanensis*. No. 7953, U. S. N. M. One-half natural size. A, Posterior view; B, external view; C, anterior view. *a*, Finger-like trochanter; *b*, great trochanter; *h*, head; *ic*, inner condyle; *oc*, outer condyle; *t*, fourth trochanter.

The pes in *Brachyceratops* consists of four functional digits and one which is vestigial. n these semiarticulated feet the phalangial formula has been determined as 2, 3, 4, 5, 0? gure 46 the foot is drawn with the toes spread wide apart, the pose being that assumed by ıtarsals I, II, and III, which are firmly united by matrix. Study of the second foot (No. ;) and of the opposing surfaces of the metatarsals lends convincing evidence that the sur- ; of their shafts were more closely applied throughout most of their length. They inter- with one another at their proximal ends and thus form a compact, strong foot.

Tarsus.—The known tarsus consists of four bones, the astragalus, calcaneum, and two tarsalia of the distal row.

The astragalus is represented by three bones, one belonging to the foot (No. 7956), a second firmly coossified with the tibia shown in figure 44, and a third, somewhat fragmentary, which was found in the float. The astragalus of No. 7956 is an elongated, rectangular, blocklike bone having a slightly rugose distal surface that is convex anteroposteriorly. The proximal surface is concave in the same diameter. The external end is thickened, but the internal end thins out to a liplike rounded end, deeply notched at the center. When articulated with the tibia (see fig. 44) it appears relatively larger than in *Triceratops*. The greatest transverse diameter of astragalus of No. 7956 is 59 millimeters, and the greatest anteroposterior diameter is 27 millimeters.

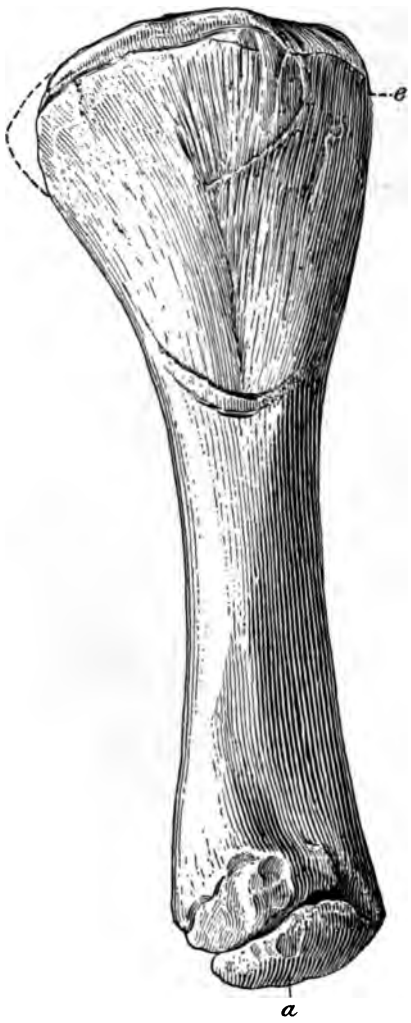


FIGURE 44.—Tibia of *Brachyceratops montanensis*. No. 7957, U. S. N. M. One-half natural size. Oblique external view. *a*, Astragalus; *e*, enemial crest.

FIGURE 45.—Fibula of *Brachyceratops montanensis*. No. 7957, U. S. N. M. One-half natural size. Lateral view. *a*, Proximal end; *b*, distal end.

The calcaneum is represented by two bones, one belonging to the foot of No. 7957 and a second to No. 7956. The calcaneum pertaining to specimen No. 7957 is the better preserved and was found in close association with the foot, as shown in figure 47. The surface opposed to the distal end of the tibia is cupped, the anteroinferior face is broadly rounded dorsoventrally, and the superior surface presents a triangular articulating surface for the distal end of the fibula. This bone has a greatest vertical diameter of about 34 millimeters; anteroposteriorly it measures 30 millimeters.

The ossified tarsal bones of the distal row are irregularly rounded discoidal elements with upper surfaces concave and lower convex. In figure 47 they are shown as found in place and in all probability are not far removed from their proper position in the tarsus. The largest articulates with the proximal end of metatarsal II, the smallest with metatarsal III (see fig. 46), to which it was found securely attached by matrix. The third tarsal was wholly in apposition to metatarsal IV.

Metatarsus.—The metatarsus, as already stated, comprises four functional metatarsals and one that is vestigial. Metatarsal I, the shortest of the functional series, is robust and has expanded articular ends, more especially the distal, which is rectangular in outline, its articular surface being cut off obliquely to the longer axis of the shaft. In the articulated foot its proximal end extends above the upper articular surface of metatarsal II and probably shows the correct articulation of these bones, for the two feet (Nos. 7956 and 7957) have these elements preserved in almost identical positions.

Metatarsal II is nearly twice the length of metatarsal I but is shorter than metatarsal III. The proximal end is expanded anteroposteriorly, and the distal end has its greatest diameter

transverse. The internal surface of the proximal end is shallowly concave for better articulation with metatarsal I. The opposite side is slightly convex and articulates with the concave surface of metatarsal III.

Metatarsal III is the longest bone of the foot and in general resembles the median element of the *Triceratops* foot. The expansion of the proximal end is chiefly anteroposteriorly, and that of the distal end, as in metatarsal II, is transverse. The distal articular ends of both metatarsals II and III of foot No. 7957 are peculiarly flattened and are not convex anteroposteriorly, as in most dinosaurian metatarsals. The ends are also cut off somewhat obliquely to the longer diameter of the shafts, their faces being directed slightly inward.

Metatarsal IV is shorter than metatarsal II and may be distinguished from the other metatarsals by the anteroposteriorly compressed shaft. The transverse diameter of the proximal end also exceeds the anteroposterior diameter. The inner side near the proximal end has a slightly concave triangular area which articulates well with the convex surface of metatarsal III. The proximal end is slightly cupped as in metatarsal IV of *Camptosaurus* and *Thescelosaurus*, for the better articulation of the distal tarsal element. The shaft, although somewhat constricted, is relatively wider than in the other metatarsals.

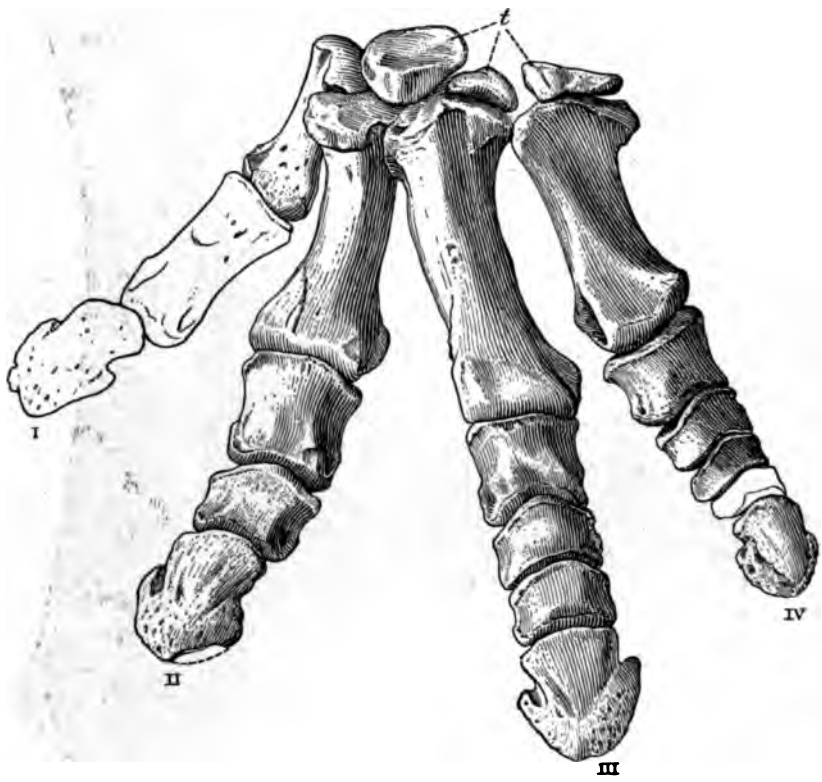


FIGURE 46.—Left hind foot of *Brachyceratops montanensis*. No. 7957, U. S. N. M. One-half natural size. Anterior view. *t*, Tarsal bones of the distal row; I, II, III, and IV, digits 1 to 4, respectively. Bones in outline have been introduced upon the evidence furnished by the foot of specimen No. 7956, shown in figure 47.

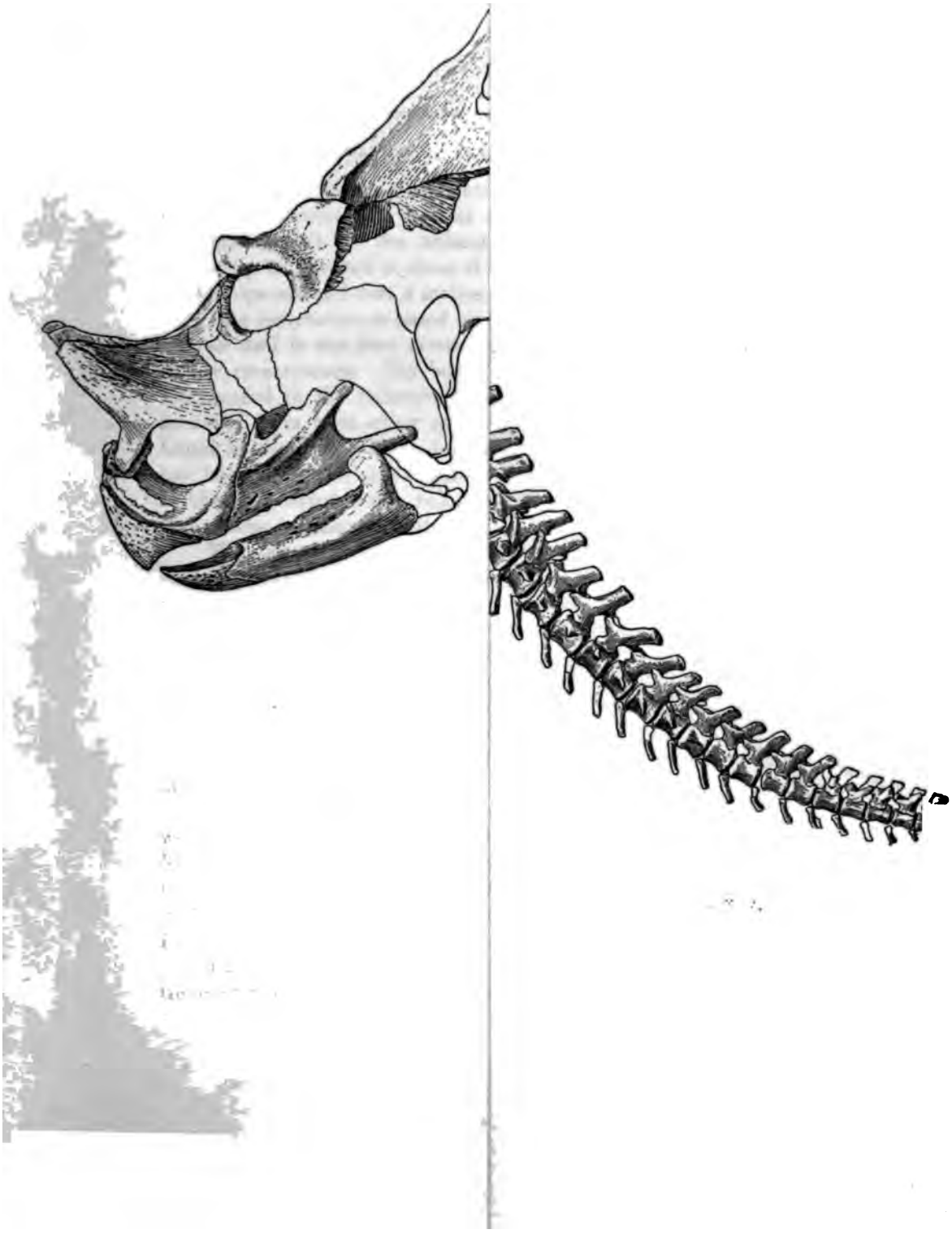
The distal face is nearly square in outline, though all four sides are decidedly concave on their median surfaces. The articular end is convex anteroposteriorly.

Metatarsal V is known only from two fragmentary ends which are regarded as representing proximal articular portions. One of these was associated but not articulated with foot No. 7957. It is a thin flattened bone with a rounded articular end that in all probability was attached to the posterior side of metatarsal IV. The distal portion is unknown.

Phalanges.—The proximal phalanges are somewhat longer than the intermediate ones. The proximal phalanx of digit I is especially elongated, equaling in this measurement the metatarsal of digit I. Its upper surface is beveled off toward the inner side of the foot. All the phalanges are flattened, blocklike elements, with concave proximal and convex distal extremities, but lacking the pulley-shaped finish of the *Camptosaurus* phalanges with their vertical interlocking keels. Many of the phalanges show shallow lateral pits for the attachment of ligaments. The second, third, and fourth phalanges of digit IV are considerably more shortened than are the phalanges of the other toes. The unguals are flattened and have broadly rounded anterior borders with pitted surfaces. As in *Triceratops* and *Stegosaurus*, in life these were probably incased in flat hoofs. Their articular ends are shallowly concave and have elon-

U. S. GEOLOGICAL SURVEY

PROFESSIO



gated oval outlines. In a general way they resemble the unguals of *Trachodon* more t of *Triceratops*, as figured by Hatcher.[1]

Measurements.—Measurements of the left hind foot of the paratype No. 7957 foll

Measurements, in millimeters, of the left hind foot of Brachyceratops montanensis (No. 7957).

	I.	II.	III.
Greatest length of metatarsals	53	92	97
Proximal end of metatarsals:			
Greatest anteroposterior diameter	27	43	36
Greatest transverse diameter	20	30	27
Distal end of metatarsals, greatest transverse diameter	30	33	34
Phalanges, greatest length:			
First row	[a] 51	34	28
Second row	[a] 37	24	20
Third row	.....	37	18
Fourth row	.....	.....	36
Fifth row	.....	.....	.....

[a] Measurements from another individual of about the same proportions (No. 7956).

RESTORATION OF BRACHYCERATOPS.

A complete skeletal restoration of *Brachyceratops montanensis*, about one-fifth natural size, is shown in Plate IV. The total length of the animal from the end of the nose to the tip of the tail is about 6 feet 9 inches, and its height at the hips about 2 feet 4 inches.

This restoration is based on the remains of several individuals and is the first attempt thus to depict one of the earlier ceratopsians. The bones drawn in outline were not represented in the collections and have been supplied in a modified form from other specimens, preferably from those found in the Judith River formation. The presacral region has been given the same number of vertebrae as are found in the articulated series belonging to the type specimen of *Triceratops brevicornus* Hatcher.

The sacrum, pelvis, femora, and tail were found in so close association that they unquestionably pertain to one individual (No. 7953, U. S. N. M.). In fact, the caudal vertebrae were nearly all articulated, and this complete series is of especial interest as giving us the first adequate conception of the ceratopsian tail. It shows this appendage to be considerably longer than has been represented in previous restorations of Lance ceratopsians. Whether this lengthening is peculiar to the primitive forms from the Judith River and Belly River formations remains to be determined.

The structure of the fore foot as shown is perhaps somewhat conjectural, although it is based on an articulated fore foot of *Leptoceratops*, a ceratopsian from the Edmonton formation of Canada, a drawing of which was generously supplied by Mr. Barnum Brown, of the American Museum of Natural History.

FIGURE 47.—Left hind foot of *Brac tanensis*. No. 7956, U. S. N. M. C size. Shown as found in place. of the distal row; *u*, ungual; I, I digits 1 to 4, respectively.

The few bones of the manus present in the collection have been inserted in accord the evidence of this articulated foot.

[1] Hatcher, J. B., The Ceratopsia: U. S. Geol. Survey Mon. 49, fig. 73 (*d*, *e*, *f*), 1907.

The animal is represented standing, with the nose thrown downward, a position that is well adapted for the most effective use of the strong nasal horn, and that also brings the head within easy feeding distance of the ground.

The fore limbs are strongly flexed, principally on the evidence of the well-developed olecranon on the ulna. The tail drops rapidly from the sacrum, its distal portion, in life, evidently dragging upon the ground. The scapula has been placed in a somewhat horizontal position well down on the side of the ribs, in accordance with the evidence of the position of this bone in several articulated skeletons of the trachodont dinosaurs. The great elevation of the transverse processes of the dorsal vertebrae, reaching nearly to the top of the spinous processes, is well shown, as is also the relative shortness in height, compared with those of the anterior part, of the spinous processes of the posterior dorsal and sacral vertebrae, which in *Triceratops* are the highest of the column. The specimen throws little light on the proper articulation of the ischia with the other elements of the sacrum, and the restoration of these bones has been made in accordance with the mounted skeleton of *Triceratops* in the United States National Museum.

A life restoration of *Brachyceratops*, about one-sixth natural size, based on the articulated skeleton (Pl. IV) is shown in Plate I. The pose is much the same as that of the skeleton.

It is the first restoration of a ceratopsian dinosaur in which an attempt has been made to indicate the nonimbricating, scalelike texture of the skin. This feature of the restored animal is based on a recently discovered specimen [1] of *Protorosaurus*, with which well-preserved impressions of the skins were found.

It appears fair to assume that all the horned dinosaurs were covered by a scaled integument, although the pattern of the scales probably varied in the different genera. In the present restoration the skin pattern is modified after the figures and description given by Lambe. The impression of the integument shows the plates to have been generally five and six sided, with a sunken peripheral margin. In size they appear to increase from below upward. Other impressions low down on the body indicate that these parts were covered with small tubercles and that the large plates were absent. The pattern of the skin as here depicted is exaggerated in the size of the plates, as it was hardly practicable to reduce them to the same scale as the model.

Following Lull in his restorations of ceratopsian heads, I have represented the gape of the mouth as being short.

RELATIONS OF BRACHYCERATOPS.

At this time it is difficult to arrive at a satisfactory conclusion regarding the true affinities of *Brachyceratops;* first, because of the fragmentary nature of some of the specimens on which the more primitive ceratopsian genera are based; and, second, because of the recent discoveries of new materials, much of which is as yet undescribed and which promises to materially change previously accepted views of relationships.

In the preliminary account [2] of *Brachyceratops* I stated that "it would appear most nearly allied to *Monoclonius*," and after an interval of more than two years still hold this opinion. Brown [3] has recently redefined the genus *Monoclonius*, and this definition, based entirely on skull characters, with two exceptions would apply equally well to the genus *Brachyceratops*. It is as follows:

> Skull small to medium sized, with three horns; nasal horn large, curved or straight, rising from middle of nasals immediately above the posterior border of the nares; supraorbital horns small or incipient and flattened on the outer surface. Nasals large; nares nearly separated by osseous septum formed by premaxillaries and nasals. Premaxillaries deep with vertical plate forming septum, nonfenestrated. Crest composed of short, broad squamosals and extension of elongate coossified postfrontals (parietals) [dermosupraoccipitals] perforated by large fenestrae; each fenestra wholly within the boundary of the postfrontal [dermosupraoccipitals]. Margin of crest crenulated, each prominence bearing a separate ossification. A pair of long curved hooklike processes on posterior border of postfrontals [dermosupraoccipitals]."

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[1] Lambe, L. M., On the fore limb of a carnivorous dinosaur from the Belly River formation of Alberta, and a new genus of Ceratopsia from the same horizon, with remarks on the integument of some cretaceous herbivorous dinosaurs: Ottawa Naturalist, vol. 27, p. 132, pl. 14, January, 1914.

[2] Gilmore, C. W., A new ceratopsian dinosaur from the Upper Cretaceous of Montana, with note on *Hypacrosaurus*: Smithsonian Misc. Coll., vol. 63, p. 9, Mar. 14, 1914.

[3] Brown, Barnum, A complete skull of *Monoclonius*, from the Belly River Cretaceous of Alberta: Am. Mus. Nat. Hist. Bull., vol. 33, pp. 549–558, Oct. 8, 1914.

Brachyceratops, however, does not have separate ossifications on the prominences arou the borders of the crest or frill, nor are there any "hooklike processes" on the median posteri border of the dermosupraoccipital. The fenestrae in the frill are decidedly smaller than any recognized species of *Monoclonius*, and it has not yet been demonstrated that *Monoclonius* has its nasal horn divided longitudinally, as in *Brachyceratops*. The latter feature would repr sent a most important structural difference, provided such a difference can be shown to exis but I am of the opinion that when juvenile specimens of *Monoclonius* are found they will al show a similar development of the nasal horn core.

Lambe[1] has proposed a division of the Ceratopsia into three subfamilies, the Centrosau rinae, the Eoceratopsinae, and the Chasmosaurinae, named from the most primitive member each group. *Brachyceratops* is included with *Centrosaurus* (regarded by Brown[2] as being synonym of *Monoclonius*) and *Styracosaurus* in the subfamily Centrosaurinae. This subfamil is characterized by genera having representatives with "small brow horns, a large nasal hor and parietal [dermosupraoccipital] expanded behind short squamosals."

An article by Barnum Brown[3] described the new ceratopsian dinosaur *Leptoceratops gracili* which he considers a primitive, aberrant type related to *Brachyceratops*. Further he say "The complete skeleton will probably show characters sufficiently diverse to warrant foundi a new family to include *Leptoceratops* and *Brachyceratops*, * * * and from the materi now available the two genera appear to be distinguished from allied genera by characters at least subfamily rank." In so far as *Leptoceratops* is concerned the proposed classification quite acceptable, but careful study of Brown's paper fails to disclose characters showing th *Leptoceratops* and *Brachyceratops* are so closely related. Certainly a comparison of the skel tal parts does not reveal such close affinities. Both, it is true, belong to the Ceratopsia and bot are diminutive members of that order, but there, for the most part, their close resemblan ends. This is clearly shown by the comparison of their more important characters in the parall columns below:

	Leptoceratops.	Brachyceratops.
Skeleton	Small	Small.
Skull	Short and deep	Short and deep.
Nasal horn	None	Well developed.
Crest	High, thin sagittal ridge	Low, obtuse sagittal ridge.
Posterior border of crest	Smooth, without median emargination	Undulating, with median emargination
Squamosal	Extending to extreme posterior border of crest.	Short, extending a little more than ha way to extreme border of crest.
Teeth	Single rooted	Not determined.
Dentary	Massive, short, and deep	Relatively slender, of medium lengt narrow.
Do	Less than 15 rows of teeth	More than 15 rows of teeth.
Splenial	Large, extending to symphysis	Not present.
Predentary	Long and narrow	Moderate length and width.
Manus	Digits I, II, and III terminating in hoofs.	Not known.
Carpals	Ossified, ulnars and radials large	Do.
Femur	Straight; fourth trochanter comparatively large.	Straight; fourth trochanter moderate developed.
Tail	Long and deep, with high, slender spines and long chevrons.	Long, with short, heavy spines and rel tively short chevrons.

Other differences might be given, for only the generic and specific characters as enume ated by Brown are contrasted above. These, however, appear to show enough fundament differences in the skeletal structure to preclude the conclusion that they are closely related.

That the genus *Brachyceratops* represents one of the more generalized forms of the Cer topsidae is apparent; that it can not be included in either the *Ceratops-Torosaurus* or the *Eocer*

[1] Lambe, L. S., On *Eoceratops canadensis* gen. nov., with remarks on other genera of Cretaceous horned dinosaurs: Canada Geol. Survey Mu Bull. 12, p. 20, May 7, 1915.

[2] Brown, Barnum, op. cit., p. 551.

[3] *Leptoceratops*, a new genus of Ceratopsia from the Edmonton Cretaceous of Alberta: Am. Mus. Nat. Hist. Bull., vol. 33, pp. 567-580, 191

tops-Triceratops phylum is also evident, for it is hardly conceivable that an animal like *Brachyceratops*, having a nasal horn split longitudinally by suture and an outgrowth from the nasal bones, could be the progenitor of later ceratopsians having this horn developed from a center of ossification distinct from the nasal bones.

Brachyceratops apparently represents a phylum commencing prior to Judith River time, which either died out before the Lance or the representatives of which have not yet been discovered.

Family TRACHODONTIDAE.

The great number of their remains appears to indicate that the trachodonts were the most abundant dinosaurs of Two Medicine time. Four genera of Trachodontidae are now generally recognized from the Judith River and Belly River formations, and these display nearly as much variety of form and structure as the contemporary Ceratopsidae. In the collection from the Two Medicine formation four distinct genera are recognized: (1) *Hypacrosaurus*, which has been regarded as the largest of all trachodonts; (2) *Stephanosaurus;* (3) a specimen which is too incomplete to describe but which apparently belongs to an undescribed genus that may be separated from the crested trachodonts (*Hypacrosaurus*, *Saurolophus*, and *Stephanosaurus*) by its possession of a long, straight ischium without terminal expansion of its distal end and with ilia that distinguish it generically from the Lance trachodonts; and (4) a very large humerus and scapula from the Two Medicine locality, comparable in its great size with a trachodont fore foot and limb from the Edmonton formation of Alberta, now in the American Museum of Natural History, New York City.

Hypacrosaurus altispinus? Brown.

Hypacrosaurus altispinus? Brown is represented in the collections by a partly disarticulated skeleton [1] (No. 7948, U. S. N. M.), the bones of which are in an excellent state of preservation. The specimen was found by Mr. Stebinger in 1912 and was collected by me the following summer from the south side of Milk River, in the NW. ¼ sec. 27, T. 37 N., R. 8 W., on the Blackfeet Indian Reservation, Teton County, Mont. (See Pl. II, *A*, p. 2.) It consists of the left ramus and jugal, two cervical processes, nine sacral centra with sacral ribs, five caudals, an anterior chevron, three posterior ribs, eight spines pertaining to the dorsal and sacral region, left ilium, both pubes, left femur, both tibiae and fibulae, both of metatarsi III, distal portion of metatarsal IV, five phalanges, both ulnae, metacarpal IV, and several fragments.

The specimen is of especial interest as greatly extending the known geologic and geographic range of the genus *Hypacrosaurus*. After a careful comparison with the description and figures of the type, I am unable to distinguish it from the only known species, *H. altispinus*, from the Edmonton Cretaceous of Canada, described by Brown.[2] The specimen is smaller and perhaps younger (as indicated by the open sutures of the skull and sacrum) than any of the typical specimens, but all of its bones, so far as they can be compared, are remarkably similar in shape and proportions to those of *H. altispinus*.

The left dentary, nearly perfect (see fig. 48), but without teeth, and the complete jugal (see fig. 49) of this specimen are all that is known of the head of *Hypacrosaurus*. Its "footed" ischium, however, suggests the probability of its having a crested skull of the *Saurolophus* or *Stephanosaurus* type.

The jugal (see fig. 49) is relatively short and in its contours and proportions is remarkably similar to the jugal of *Stephanosaurus marginatus* Lambe. It has a greatest length of 238 millimeters and a depth at center of 180 millimeters.

As compared with the Lance trachodonts the dentary of the present specimen is remarkably slender. (See fig. 48.) Its greatest length is 544 millimeters; its depth at the middle of the magazine is 86 millimeters; the distance in front of the magazine to the anterior end of the sym-

[1] Gilmore, C. W., A new ceratopsian dinosaur from the Upper Cretaceous of Montana, with note on *Hypacrosaurus:* Smithsonian Misc. Coll., vol. 63, No. 3, p. 10, 1914.

[2] Brown, Barnum, A new trachodont dinosaur, *Hypacrosaurus*, from the Edmonton Cretaceous of Alberta: Am. Mus. Nat. Hist. Bull., vol. 32, pp. 395–406, 1913.

FIGURE 48.—Left dentary of *Hypacrosaurus altispinus?* Brown. No. 7948, U. S. N. M. One-fourth natural size. Internal view.

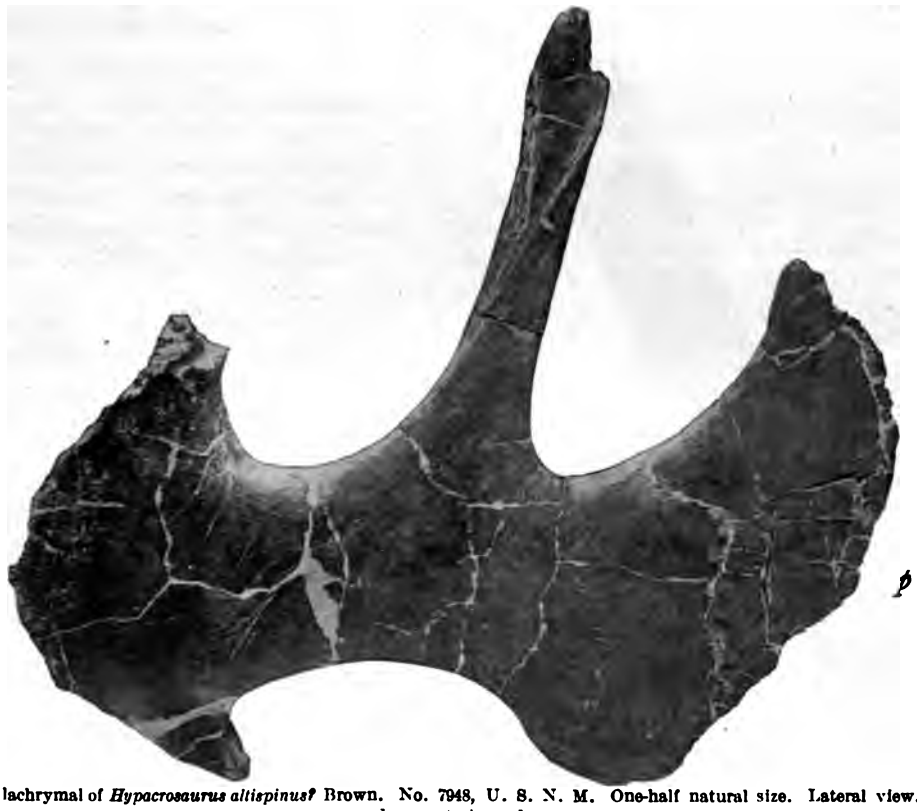

FIGURE 49.—Left lachrymal of *Hypacrosaurus altispinus?* Brown. No. 7948, U. S. N. M. One-half natural size. Lateral view. *a*, Anter end; *p*, posterior end.

FIGURE 50.—Right ilium of *Hypacrosaurus altispinus?* Brown. No. 7948, U. S. N. M. One-eighth natural size. Lateral view.

FIGURE 51.—Left pubis of *Hypacrosaurus altispinus?* Brown. No. 7948, U. S. N. M. One-fourth natural size. External view.

FIGURE 52.—Anterior caudal vertebra of *Hypacrosaurus altispinus?* Brown. No. 7948, U. S. N. M. One-half natural size. Viewed from left side.

physial surface is 120 millimeters; the length of the dental magazine is 293 millimeters. It has 39, possibly 40, alveolar grooves.

The distance from the front of the dental magazine to the end of the symphysial surface is relatively shorter and has a more abrupt downward deflection in the Judith River forms than it has in those from the Lance.

The ilium (see fig. 50) has a strongly arched superior border, with a preacetabular process compressed and of almost uniform transverse thickness; the pubis (see fig. 51) is comparatively short and has its anterior portion broadly expanded.

Well-preserved anterior and median caudal vertebrae are shown in figures 52 and 53. The

FIGURE 53.—Median caudal vertebra of *Hypacrosaurus altispinus?* Brown. No. 7948, U. S. N. M. One-fourth natural size. Viewed from right side.

spines are high and strongly inclined backward. The centrum of the anterior caudal is more than one-quarter of the total height of the vertebra. The median caudal shows a ened centrum with shallowly biconcave ends. Well-defined chevron facets are pr both back and front.

The following measurements show the resemblance of the Milk River specimen (N U. S. N. M.) to the type (No. 5204) and paratype (No. 5272) of *H. altispinus* in the A Museum of Natural History:

Comparative measurements, in millimeters, of specimens of Hypacrosaurus altispinus.

	Am. Mus. Nat. Hist. Type No. 5204.	U
Ilium:		
Extreme length	1,060	
Height	320	
Pubis:		
Greatest length at center		
Narrowest width of blade	120	
Greatest width of blade		
Caudal vertebra:		
Length of centrum, first or second	90	
Width of centrum	180	
Height over all		
Height of spine above neural canal		
	Paratype No. 5272, Am. Mus. Nat. Hist.	
Ulna, length	750	
Metacarpal IV, length	280	
Femur, length		
Tibia, length	1,080	
Fibula, length	1,000	
Metatarsal III, length	430	

Stephanosaurus marginatus? (Lambe).

The posterior portion of a right dentary without teeth (No. 8052, U. S. N. M.) prov identified as pertaining to *Stephanosaurus marginatus* (Lambe) was obtained from Medicine River locality during the summer of 1913. (See fig. 54.)

The general proportions of this bone, with high coronoid process without marke posterior expansion of its upper extremity, agrees perfectly with the dentary of *S. m* as figured by Lambe [1] from the Belly River formation on Red Deer River in Alberta, C

A second specimen (No. 7703, U. S. N. M.), provisionally referred to this genus and was obtained by Mr. Stebinger in 1912 from the Two Medicine formation on Two River. It consists of a fragment of a dentary containing several teeth whose lateral are decorated with small rounded projections or pappillae from a point near the ape ward to the place where the crown begins to narrow again.

Trachodont gen. and sp. undet.

A fragmentary skeleton (No. 8058, U. S. N. M.) of a trachodont dinosaur from Medicine River locality is of interest as having ischia of the Lance trachodont style (that out expanded distal extremities) associated with ilia that resemble most nearly thos crested forms like *Saurolophus* and *Hypacrosaurus*. Whether these remains repr

[1] Lambe, L. M., On Vertebrata of the Mid-Cretaceous of the Northwest Territory: Contr. Canadian Paleontology, vol. 3, pt. 2, p. 73, pl. 4,

undescribed genus or pertain to one of the described members of this group that have be based on skulls it is not possible to say at this time.

The specimen was found about a mile below the abandoned ranch buildings of John F wards, on the south side of the river, at the base of the high exposures (about the middle of t Two Medicine formation). (See fig. 1, p. 2.) The bones received are two ilia, two isch two dorsal and three caudal vertebrae, three chevrons, and fragmentary parts.

The ischia (see fig. 55) are slenderer than those in any described trachodont, having extreme length of 880 millimeters and a diameter across the iliac and pubic heads of 230 mi meters. The most striking feature of the ischia is the presence on the inferior border of t expanded end of an elliptical foramen-like notch (*f*, fig. 55). In the Lance trachodonts th is usually a slight indentation at this point, and in *Saurolophus* the place is entirely inclos

FIGURE 54.—Right dentary of *Stephanosaurus marginatus?* (Lambe). No. 8052, U. S. N. M. One-half natural size. Internal view.

by bone forming a foramen. In *Hypacrosaurus* the ischium shows a long, shallow indentati more like that in theLance trachodonts.

Below the expanded proximal end the shaft contracts abruptly and continues as a lo slender rod that expands only slightly toward the distal end. The inner surface of the dis two-thirds is longitudinally striated, indicating the ligamental union with its mate of the op site side. The ilium (see fig. 56) has about the same outline and form as in *Saurolophus* a *Hypacrosaurus*. Vertically it is narrower than in *Hypacrosaurus*, and the preacetabular proc is flattened and is relatively longer and narrower. It appears to agree with Cope's brief descr tion [1] of the ilium of *Pteropelyx grallipes* Cope. Whether it should be referred to that fo remains to be determined. Measurements of the right ilium are given below.

	Millimeters.
Greatest length	880
Greatest height	205
Depth at center of acetabulum	170
Length of preacetabular process	405
Length of postacetabular process	240

[1] Cope, E. D., Notes on the Dinosauria of the Laramie: American Naturalist, vol. 23, p. 904, 1889.

Trachodont gen. and sp. undet.

A scapula and humerus (No. 7955, U. S. N. M.) of an exceedingly large trachodont reptile were collected on Two Medicine River. (See Pl. II, *B*, and fig. 1, p. 2.) While the material is insufficient to determine the genus and species to which it belongs, the specimen is of interest on account of its resembling most nearly a fore limb and foot from the Edmonton Cretaceous of Canada, now in the American Museum of Natural History.

FIGURE 55.—Left ischium of unidentified trachodont reptile. No. 8058, U. S. N. M. One-eighth natural size. External view. *f*, Notch; *i*, ilium articulation; *p*, pubic articulation.

The measurements, however, show that the specimen has a smaller scapula and a much longer humerus than *Saurolophus osborni*,[1] and these differences at once separate it from that genus.

Comparative measurements, in millimeters, of Trachodon sp., Trachodon annectens, and Saurolophus osborni.

	Type: *Trachodon annectens* (No. 2414, U.S.N.M.).	Trachodon sp. (No. 7955, U.S.N.M.).	Type: *Saurolophus osborni* (No. 5220, Am. Mus. Nat. Hist.).
Greatest length of scapula	810	910	979
Greatest width of blade of scapula	200	208	230
Greatest length of humerus	501	[a] 760	500
Greatest transverse diameter, distal end	105	180	.....

[a] Estimated.

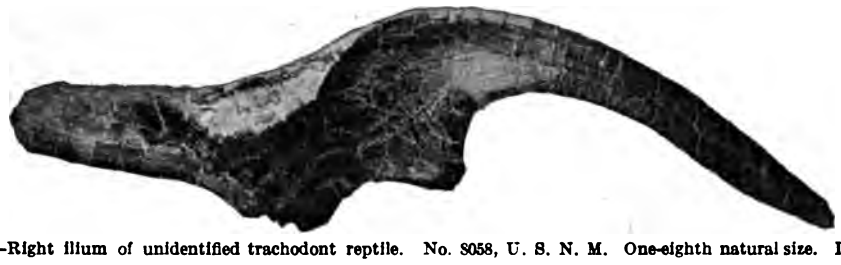

FIGURE 56.—Right ilium of unidentified trachodont reptile. No. 8058, U. S. N. M. One-eighth natural size. Lateral view.

Family ANKYLOSAURIDAE.

Europlocephalus sp.

A coossified transverse row of dermal plates or scutes (see fig. 57) is identified as pertaining to this genus. The keeling of the scutes differs somewhat from a row of plates pertaining to the type of *Europlocephalus tutus* Lambe, from Belly River, Canada, as figured by Lambe.[2]

[1] Brown, Barnum, The skeleton of *Saurolophus*, a crested duck-billed dinosaur from the Edmonton Cretaceous: Am. Mus. Nat. Hist. Bull., vol. 32, p. 392, 1913.

[2] Lambe, L. M., On Vertebrata of the Mid-Cretaceous of the Northwest Territory: Contr. Canadian Paleontology, vol. 3, pt. 2, pl. 12, figs. 3, 4, 1902.

The specimen was found on Milk River, a short distance from the place where the type of *Brachyceratops montanensis* was discovered, at a slightly higher horizon. It consists of two entire scutes and a portion of a third, all firmly coossified. The under surface is arched transversely and probably represents the first row of plates posterior to the skull. The plates are subrectangular in outline, wider than long, with a raised median portion that is longer than wide, and is surmounted by a blunt nodelike spine asymmetrically placed, as contrasted with the sharply keeled scutes of *Euoplocephalus tutus* Lambe.

The union of the plates on the dorsal surface is plainly discernible, but the sutures on the ventral side are entirely obliterated. Vascular markings are conspicuous on the upper surfaces, especially on the raised median portions. (See fig. 57.) Although this specimen is identified as pertaining to the genus *Euoplocephalus*, it might with equal propriety be referred to *Ankylosaurus*, or it may represent an undescribed form.

FIGURE 57.—Dermal plates of *Euoplocephalus* sp. No. 7943, U. S. N. M. One-third natural size. Dorsal view.

Class CHELONIA.

Basilemys sp.

The genus *Basilemys* is represented by fragmentary parts of the carapace and plastron, several vertebral centra, one humerus, and fragments of other limb bones, all regarded as belonging to one individual (No. 8024, U. S. N. M.).

Dr. O. P. Hay was kind enough to spend some time in studying the specimen, and he is of the opinion that it belongs either to *Basilemys nobilis* Hay, the type of which is from the beds in New Mexico described by Brown as the Ojo Alamo formation, or to a closely related species. *B. nobilis* has as its distinguishing character a high ridge, or wall, around the upper side of the hinder lobe of the plastron. In the specimen this ridge is high in front but is reduced farther behind and is rather flat. This change may possibly be due to individual variation.

The specimen was found in sec. 27, T. 37 N., R. 8 W., on the south side of Milk River, somewhat below the horizon in which the *Hypacrosaurus* skeleton (No. 7948) was obtained. The specimen is of interest as apparently corroborating the dinosaurian evidence for the correlation of the Belly River formation with Brown's Ojo Alamo formation.[1]

[1] Sinclair, W. J., and Granger, Walter, Paleocene deposits of the San Juan Basin, N. Mex.: Am. Mus. Nat. Hist. Bull., vol. 33, pp. 302, 303, 1914.

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DEPARTMENT OF THE INTERIOR
FRANKLIN K. LANE, Secretary

UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, Director

Professional Paper 104

THE GENESIS OF THE ORES AT TONOPAH, NEVADA

BY

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AND
FRANCIS B. LANEY

[In cooperation with the Bureau of Mines]

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THE GENESIS OF THE ORES AT TONOPAH, NEV/

By EDSON S. BASTIN and FRANCIS B. LANEY.

INTRODUCTION.

In the spring of 1915, while engaged in a study of silver enrichment for the United States Geological Survey, Mr. Bastin spent a month at Tonopah, Nev., in studying the ores and their mode of occurrence. At about the same time Mr. Laney was directed by the United States Bureau of Mines to make collections of Tonopah ores and to study their mineralogy in connection with the researches of that Bureau on their metallurgic treatment. To avoid duplication of effort and to secure the added fruitfulness which should follow the concentration of more than one mind on a scientific problem, it was decided to combine these efforts in so far as the two fields of research overlapped. The paper accordingly presents the results of informal cooperation between the Geological Survey and the Bureau of Mines.

The investigation was intended to supplement the important work of Spurr [1] and Burgess [2] by applying to the ores methods of microscopic study which were not in general use by economic geologists at the time their reports were prepared, but which, in other districts, have proved of material assistance in the interpretation of ore genesis.

For the structural observations a
cussion of the mine waters the senio
responsible; for the detailed miner
microscopic studies both author
sponsible. They are indebted to
Palmer, of the United States Geol
vey, for careful analyses of samp
mine waters and for chemical and r
studies, and to Messrs. F. L. Ra
Adolph Knopf, also of the Survey, f
criticisms and suggestions.

The mine operators and others i
gave generously of their time and t
edge and contributed many choice
in furtherance of the work. To
writers' sincere thanks are offered.

THE TONOPAH DISTRICT.

The Tonopah mining district i
known to require an extended
From the discovery of its ores in 19
put has increased year by year un
its production of silver was excee
United States only by that of
metal output since 1904 is shown in
ing table, compiled by V. C. Heik
Geological Survey:

Gold, silver, copper, and lead produced in Tonopah district, Nev., 1904–1916.

Year.	Number of producers.	Ore.	Gold.	Silver.	Copper.	Lead.
		Short tons.		*Fine ounces.*	*Pounds.*	*Pounds.*
1904	10	22,703	$386,526	2,119,942	.....	.....
1905	12	91,651	1,206,345	5,369,439	.....	.....
1906	9	106,491	1,304,677	5,697,928	.....	.....
1907	10	214,608	1,183,628	5,370,891	5,939	195,508
1908	13	273,176	1,624,491	7,172,396	.....	.....
1909	9	278,743	1,400,361	7,872,967	1,784	1,488
1910	18	365,139	2,303,702	10,422,869	942	6,902
1911	19	404,375	2,366,495	10,868,268	.....	.....
1912	17	479,421	2,223,878	10,144,987	14	700
1913	32	574,542	2,613,843	11,563,437	1,150	9,001
1914	23	531,278	2,648,833	11,388,452	2,284	924
1915	22	516,837	2,228,983	10,171,374	.....	.....
1916	21	455,140	1,941,441	8,734,726	.....	.....
	.....	4,313,604	23,433,203	106,897,676	12,113	214,523

[1] Spurr, J. E., Geology of the Tonopah mining district, Nev.: U. S. Geol. Survey Prof. Paper 42, 1905; Geology and ore depo
Nev.: Econ. Geology, vol. 10, pp. 713–769, 1915.
[2] Burgess, J. A., The geology of the producing part of the Tonopah mining district: Econ. Geology, vol. 4, pp. 681–712, 1909.
[3] Heikes, V. C., U. S. Geol. Survey Mineral Resources, 1914, pt. 1, p. 702, 1915; idem, 1915, pt. 1, p. 647, 1916.

The copper and lead came from properties closely adjoining the district. During the years represented in the table dividends were paid amounting to $21,000,000.

The average ratio of the gold to the silver in ounces recovered during this period was about 1:98.

The total average recovery value per ton of the ore produced in 1913 was $16.71, in 1914 $16.84, and in 1915 $14,30. Most of the ore mined is treated by cyanidation, with or without concentration. It is stated that in certain plants ore assaying as low as $8 a ton can under certain circumstances be profitably treated.

STRATIGRAPHY.

It was not the writers' purpose in visiting Tonopah to review the work of Spurr and of Burgess on the age and mutual relations of the rock formations of the district, nor would this have been possible in the short time available for field work, as will be readily appreciated by anyone familiar with the remarkable complexity of the geology. The divergent views of Spurr and Burgess have been summarized with unusual clearness by Augustus Locke.[1] Locke's own views are so nearly in harmony with those of Burgess that it appears unnecessary to present them separately. The following brief summary of the major stratigraphic features of the district will assist in understanding the data on the genesis of the ores presented in this paper.

The Tonopah district is underlain by a thick series of rocks that are products of volcanic activity and are believed to be of Tertiary age. Broadly classified, these rocks consist of a lower series, mostly rhyolitic, which is overlain by two andesites, distinguished as "earlier" (now termed Mizpah trachyte by Spurr) and "later (now termed Midway) andesite." The "later andesite" is overlain

Geologic formations at Tonopah, Nev.

Origin and relative age according to Spurr.	Approximate stratigraphic succession.	Origin and relative age according to Burgess.
11. Intrusive as volcanic necks.	Brougher dacite and Oddie rhyolite.	9. Surface flows and the conduits through which the lavas rose.
10. Surface flow.	Basalt.	8. Surface flow.
8b. Intrusive.	Tonopah rhyolite of Spurr in northern part of area.	6b. Surface flows.
9. Lake deposits of volcanic material.	Siebert tuff.	7. Lake deposits of volcanic material.
8a. Intrusive, surface flows and tuffs.	Tonopah rhyolite of Spurr in southern part of area.	6a. "Surface flows of rhyolites, and breccias." Not separately considered.
7. Tuffs and mud flows.	Fraction dacite breccia.	
6. Volcanic necks and possibly some surface flows.	Heller dacite.	
5. Surface flow.	Midway andesite or "later andesite."	5. Surface flow.
1b. Surface flow.	Mizpah trachyte or "earlier andesite."	4. Surface flows.
4. Intrusive sheet.	West End rhyolite or "upper rhyolite."	3. Surface flows.
3. Intrusive sheet with many inclusions.	Montana breccia.	Not specifically mentioned but evidently classed as surface volcanic rocks. (See Burgess, J. A., op. cit., p. 682.)
1a. Basal phase of Mizpah trachyte flow.	Glassy trachyte.	
2. Flat-lying intrusive.	Sandgrass or "calcitic" andesite.	2. Surface flow.
8c. Intrusive with "autobrecciation."	Lower rhyolite.	1. Complex of tuffs, breccias, and flows.

[1] The geology of the Tonopah mining district: Am. Inst. Min. Eng. Trans., vol. 43, [illegible], 1912.

by rhyolite, lacustrine tuffs, and thin flows of basalt. In spite of complicated faulting most of the volcanic formations are rather flat-lying. The middle column of the table on page 8 shows the formations that have been recognized, arranged in the normal order of superposition. In the left-hand column is given Spurr's latest interpretation of their origin and age relations, and in the right-hand column Burgess's interpretation. The numbers indicate the relative ages under the two interpretations; formations that are regarded as contemporaneous are given the same number but differentiated by letter, as 8a, 8b. The two interpretations differ materially, most of the rocks which Spurr regards as flat-lying intrusive rocks being interpreted by Burgess as flows poured out upon ancient surfaces.

The decision between these two interpretations must be left to future students of Tonopah geology. Successful refutation of the detailed work of Spurr and his associates must be founded on observations comparable with theirs in detail and comprehensiveness.

RELATIONS OF ORES TO INCLOSING ROCKS.

The bulk of the metal production of the district has come from ore bodies lying wholly within the Mizpah trachyte ("earlier andesite"). Within recent years, however, as the result of deeper development and underground exploration of new territory, an increasing percentage of the output has come from ore bodies bounded on one or both sides by other formations. Many of the veins, for example, whose upper portions are wholly in the Mizpah trachyte have at greater depth one or both walls of West End rhyolite. Spurr[1] believes that the productive veins are of several ages and classifies them as first-period and second-period veins, the latter with four subclasses. He recognizes also third-period veins, which are not productive. The veins of the first period he believes are older than the Montana breccia and West End rhyolite; those of the second period are younger than these formations; and both sets are older than the "cap rock" or Midway andesite.

The writers had little opportunity to study in the field the structural evidence on which Spurr bases his classification. Locke[2] says: "There is no mineralogical distinction whatever to be made between many veins which, according to the hypothesis [Spurr's], should belong to different periods." The writers' observations tend to indicate at least the approximate correctness of Locke's statement. The principal productive veins of the region show notable similarity in the minerals present and in the mutual relations of these minerals. The ore of the Belmont vein, for example, which Spurr classes as a first-period vein, is practically identical in mineral composition with that of the MacNamara and Fraction veins, which he classes as second-period veins. Mineralogic differences between veins of supposed different ages are commonly no greater than may be observed in different parts of one continuous vein. In most of the "first-period" veins there is little evidence of fracturing of the ore and filling of the fractures by later ore except that resulting from downward enrichment. Upon the sole basis of the mineral composition and texture of the primary ore there would be little reason for the impartial geologic observer to regard the principal productive veins as of more than one age. Mineralogic similarity can not, however, be taken as proof of contemporaneity, for in a region where there has been recurrent volcanic activity it is possible if not probable that similar mineralization might take place at more than one period. Structural observations must furnish the final test.

In the descriptions here given the ores of the principal productive veins are described as a unit but without implication of precise equality in age. The wolframite of the Belmont vein is an exception, for it is shown by textural relations to be somewhat later than the silver ore with which it is associated.

As emphasized by Spurr[3] the ores of Tonopah are in the main replacement deposits along sheetlike zones of fracturing. They are therefore typical replacement veins. Every gradation may be traced from heavy sulphide ore into slightly replaced wall rock. Ore-cemented breccias, true crustification, comb structure, and other features characteristic of

[1] Spurr, J. E., Geology and ore deposits at Tonopah, Nev.: Econ. Geology, vol. 10, pp. 751–760, 1915.

[2] Locke, Augustus, The geology of the Tonopah mining district: Am. Inst. Min. Eng. Trans., vol. 43, p. 164, 1912.

[3] Spurr, J. E., Geology of the Tonopah mining district, Nev.: U. S. Geol. Survey Prof. Paper 42, p. 84, 1905.

ng of open spaces are rare or developed
ı a small scale. Banding somewhat re-
ıg true crustification, which is locally
:uous, is possibly to be explained by dif-
ı during replacement.
; of the veins dip steeply, but some, like
st End and MacNamara, are only moder-
ıclined.

DIVERSITY IN MINERALIZATION.

.tever may be the differences in age
the veins of Tonopah, it is certain at
hat most of the ores represent the net
of several successive geologic processes.
y of their texture and mineralogy makes
ible to group the ore minerals according
r relative ages and to reach conclusions
rd to the nature of the processes respon-
›r the deposition of each group.
solutions that deposited the great bulk
minerals of the Tonopah ores were, it is
:d, exudations from cooling, buried
of igneous rock or magma. In express-
s view the writers accept the opinion of
for the Tonopah district and align their
sions with the trend of opinion among
:an geologists in regard to the genesis of
ajority of precious-metal lode deposits.
:cumulation of independent evidence of
n origin would have involved structural
ratigraphic studies for which the writers
ttle opportunity. Such mineralization
monly termed primary, but the writers
to use the term hypogene, proposed by
me.[2] Solutions coming from great
ı within the earth and having a general
d flow will therefore be termed hypogene
›ns and the work they accomplished hy-
ɜ mineralization.
ɜr the hypogene mineralization the slow
al of the covering of volcanic rocks by
ı exposed the upper parts of many of the
to the action of the air and of waters of
ɜ origin. By the combined attack of these
upon the upper parts of the hypogene ore bodies, silver and other metals were dissolved. These metals were carried downward in solution and eventually redeposited, commonly in fractures or vugs in the hypogene ores. These are the processes commonly referred to as "oxidation" and "enrichment," but they will be referred to collectively in this paper as supergene mineralization.[3]

Although supergene mineralization has played an interesting part in the genesis of certain of the Tonopah ores, it appears to have been quantitatively much less important than the hypogene mineralization. Most of the ore bodies in which it was most prominent are worked out, and the principal dependence of the mines to-day is upon ores that, the writers believe, are almost wholly of hypogene origin.

HYPOGENE MINERALIZATION.

The hypogene ores will be considered first, because they are at present the principal economic resource of the camp and are the parent type from which the supergene ores were derived.

HYPOGENE ORE TEXTURES.

The ores of Tonopah occur in veins that were formed mainly by replacement[4] of the country rocks along zones of closely spaced fracturing. Ore deposition in open spaces was an accompanying but minor process. In places, conspicuous slip planes, accompanied by much gouge, limit or traverse the ore bodies, but commonly the ore bodies are without definite walls on one or on both sides.

LARGER TEXTURAL FEATURES.

The observations here recorded on the larger textural features of the hypogene ores were mainly incidental to the microscopic studies. A complete study of the larger vein textures was not attempted.

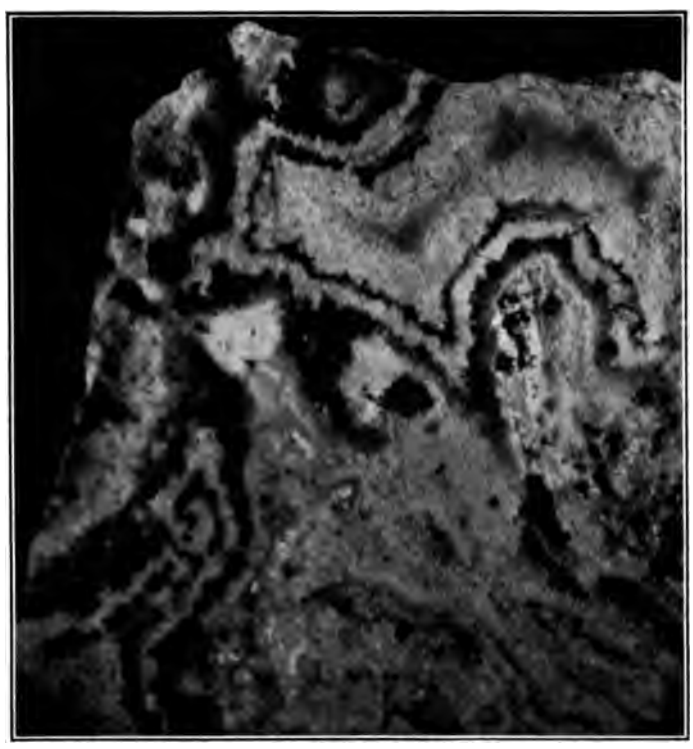
Banding in the ores was particularly conspicuous in parts of the Murray veins and commonly presents the appearance shown in

Liesegang (Geologische Diffusionen, Dresden, 1913) has shown
ın phases of banded structure may be produced by rhythmic
ion during the diffusion of a solution into some medium with
eacts chemically, or by simultaneous diffusion of two mutually
g solutions into an inert medium. It is highly probable that
ıe banding observed in ores formed by replacement has devel-
ıs way.

[2] me, F. L., Copper deposits near Superior, Ariz.: U. S. Geol. ull. 540, p. 152, 1914.

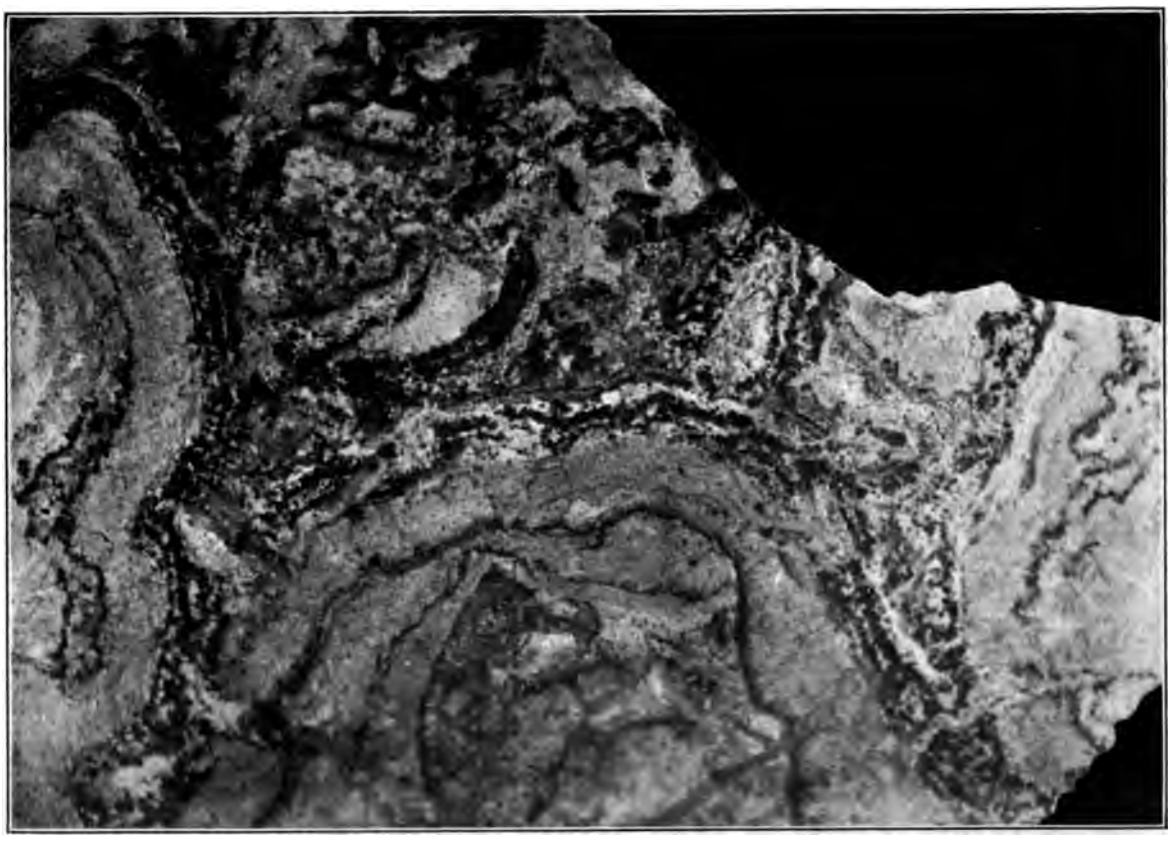
[3] Idem, p. 153. "The suggestion is offered that minerals deposited by generally downward-moving and initially temperate solutions may be termed supergene minerals."

[4] The term "replacement," as used by most economic geologists, signifies the removal of material by solution and the immediate deposition of different material in its place—either the removal of rock minerals and the deposition of ore minerals or the removal of one ore mineral and the deposition of another.



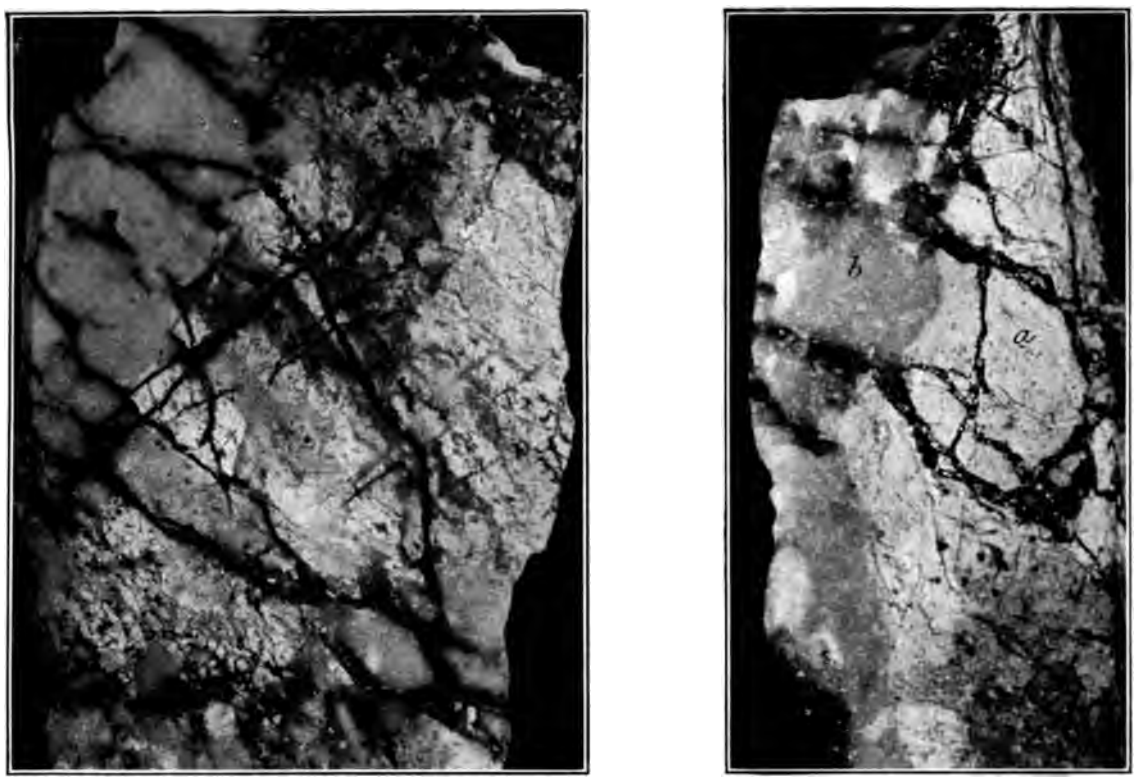
A. BANDED HYPOGENE ORE.

Enlarged 1½ diameters. The light-gray areas are mainly a fine intergrowth of ferruginous rhodochrosite and quartz; the dark-gray to black areas are mainly quartz carrying hypogene sulphides in numerous very minute grains. The radial structure of some of the rhodochrosite-quartz intergrowths at right angles to the banding is dimly shown. Belmont vein, 1,000-foot level.



B. BANDED HYPOGENE ORE.

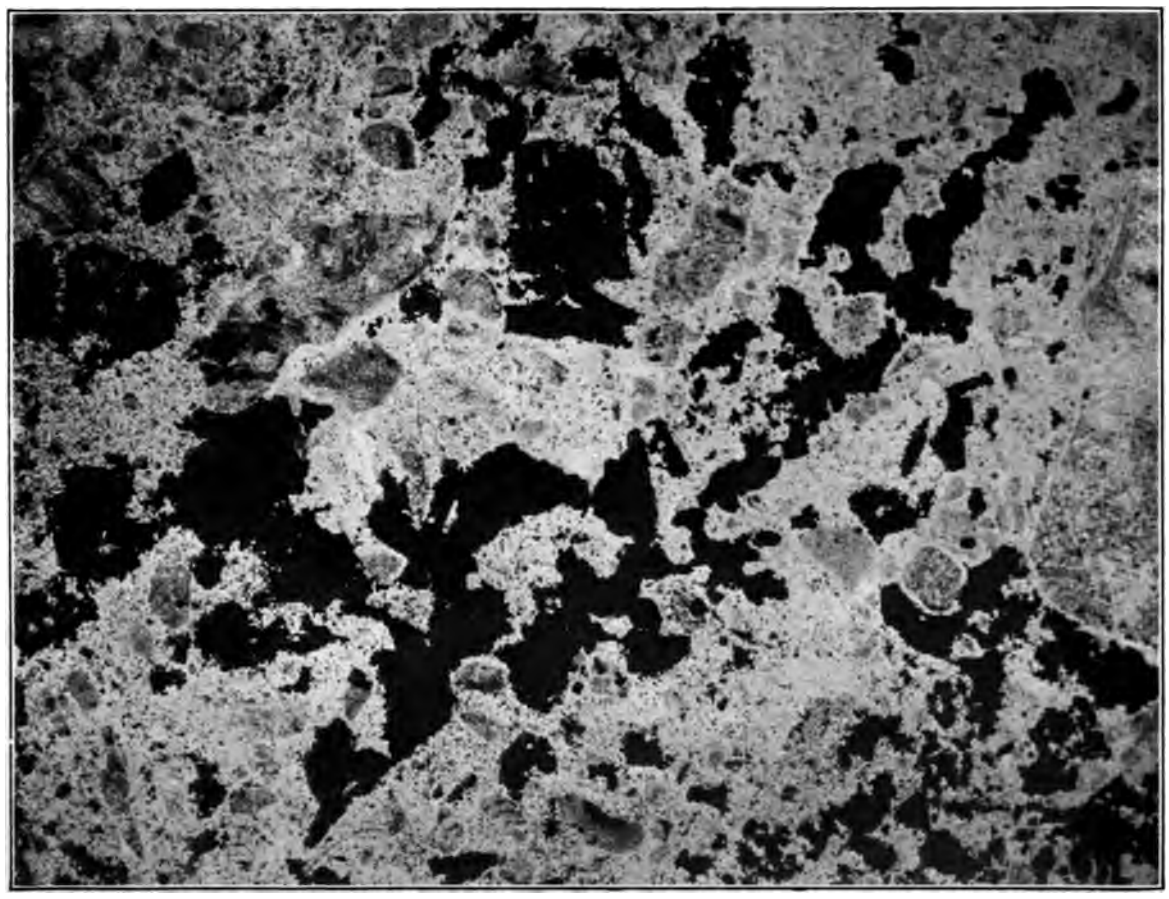
Murray vein, Tonopah Extension mine, just below 950-foot level. One-half natural size.



A. *B.*

A, B. SUPPOSED HYPOGENE VEINLETS OF PYRARGYRITE.

The veinlets pass from areas of partly altered wall rock (*a*) into quartz areas (*b*) and become less well defined in the quartz. Tonopah Extension mine, exact location uncertain. Natural size.



C. BRECCIA OF QUARTZ AND SERICITIZED WALL ROCK PARTLY REPLACED BY PYRARGYRITE (BLACK).

Photomicrograph of polished surface of ore. Tonopah Extension mine, exact location uncertain. Enlarged 25 diameters.

Plate I, *A*. Most of the lighter areas are a microscopic intergrowth of rhodochrosite and quartz; the darker areas are quartz carrying sulphides in a very fine state of division. Plate I, *B*, shows a similar structure in ore of identical appearance from the Belmont vein. In many places in both veins the banding is concentric around fragments of wall rock (probably silicified rhyolite), one of which, partly replaced by quartz, is shown below the

FIGURE 1.—Rudely concentric arrangement of sulphides around angular fragment of wall rock. One-half natural size. Belmont vein, 1,000-foot level. Sketched by E. S. Bastin.

center of Plate I, *B*. The demarcation of the light and dark bands is in places sharp but elsewhere vague. The bands may be a millimeter or less in width and confined to those parts of the matrix immediately bordering the fragments, or they may be fairly wide, as shown in Plate I. Scattered grains of pyrite are abundant in the rhyolite fragments but are absent from the ore surrounding them. The fragments are commonly angular, but some show evidences of gradual replacement by the fine quartz-rhodochrosite intergrowth. The arrangement of the black sulphide-rich portions around a wall-rock fragment in the Belmont vein is sketched in figure 1.

The concentric arrangement of many of the bands around angular fragments of wall rock favors their interpretation as true crustification. As banding of somewhat similar appearance may be developed in ores that have been formed solely by replacement, in the absence of any but very minute openings, it is difficult to exclude the possibility that some of the banding in the Tonopah ores may have originated during the replacement of a matrix of crushed rock in which larger fragments of wall rock were embedded. Undoubted crustification is locally observed in narrow veinlets traversing the wall rocks, as sketched in figure 2.

HYPOGENE (?) VEINLETS AND "BRECCIAS" OF PYRARGYRITE.

A number of specimens of rich ore obtained through the courtesy of Mr. John G. Kirchen show veinlets, mainly of pyrargyrite, traversing quartz and partly silicified wall rock. These specimens came from the Tonopah Extension mine, but their exact location in the mine is uncertain. The appearance of sawed faces is shown in Plate II, *A* and *B*. As shown particularly well in Plate II, *B*, these veinlets pass from areas of only partly silicified wall rock (*a*) into areas of quartz (*b*) that apparently represent completely silicified wall rock. Upon entering the quartz the veinlets become somewhat less well defined. Thin sections across the contact between the partly silicified and completely silicified wall rock show under the microscope that the veinlets continue with little change of form from the partly altered rock into the quartz and that they were formed after the silicification that developed the quartz areas. The veinlets are planes of minor fracturing, along which pyrargyrite has been deposited along minute fractures partly filled with fragments of quartz and altered wall rock (mainly sericite and pyrite). Some pyrargyrite has replaced the sericitized fragments and some has filled small quartz-lined vugs. In places some pyrite is so intergrown with pyrargyrite as to suggest that both were deposited at the same time. Pyrargyrite

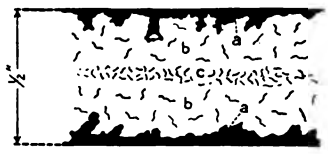


FIGURE 2.—Crustification in small veinlet traversing wall rock. Natural size. a, Sulphides; b, quartz; c, center of veinlet. Belmont vein, 1,000-foot level. Sketched by E. S. Bastin.

not confined to the veinlets, but occurs also as small patches of irregular outline scattered through and evidently replacing the partly altered bordering rock.

Areas showing pyrargyrite veinlets of the type just described or showing minute quantities of pyrargyrite replacing altered rock are closely associated with areas as much as inches across of what appears to be a breccia of pyrargyrite fragments in a gray siliceous

matrix. The pyrargyrite fragments are at most 1 centimeter across. When viewed in detail under the microscope the pyrargyrite areas are seen to have irregular outlines, as shown in Plate II, *C*, and to be in the main formed by the replacement of a breccia of quartz and sericitized wall rock. The fragmental appearance is due to the fact that certain fragments in this breccia which were evidently more susceptible to replacement than the matrix and other fragments have been almost completely replaced by the pyrargyrite.

Reliable criteria for determining whether these pyrargyrite veinlets and breccias were deposited by hypogene or by supergene solutions seem to be lacking. They may represent an early step in the extensive replacement of wall rock by an association of quartz and pyrargyrite of the type shown in Plate III, *A*, which may be very uniform in character through several cubic inches and is regarded by the writers as probably hypogene. Furthermore, most deposits of pyrargyite and other silver minerals in late fractures in the Tonopah ores can be cleanly stripped from the walls of such fractures, and the walls appear to have undergone no replacement. Such deposits are interpreted as supergene and are quite different from the pyrargyrite deposits described in the present section. The writers are inclined to believe, therefore, that these unusual pyrargyrite veinlets and breccia-like deposits are hypogene, though recognizing that the evidence is not conclusive.

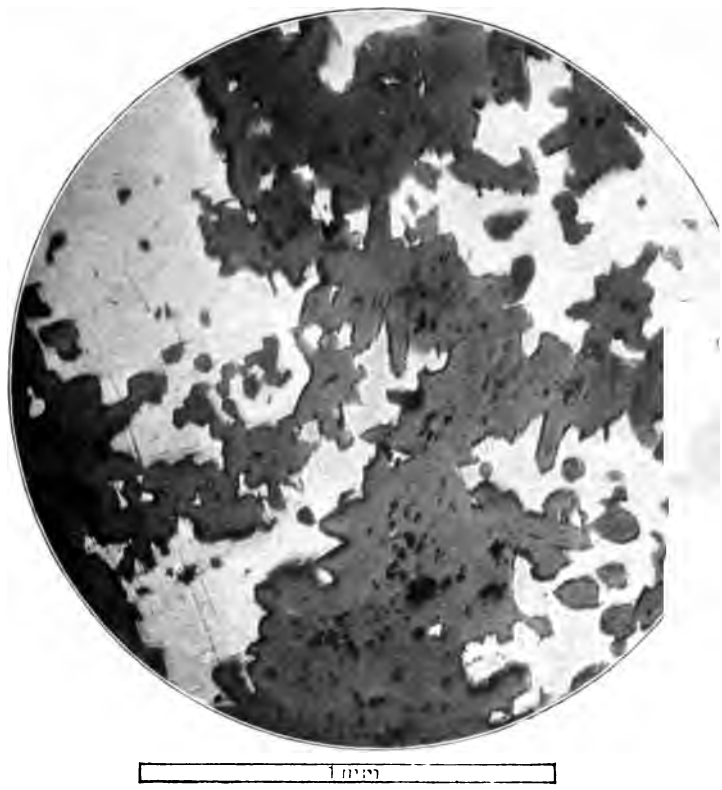
MINUTE TEXTURAL FEATURES.

The microscopic study of the ores reveals minute textural relations, not otherwise recognizable, that are of great importance in interpreting their genesis. It shows repeatedly and with especial clearness that the primary or hypogene mineralization was not a simple, brief event but was a process of considerable duration accomplished by solutions whose composition was not at all times the same. Ore minerals deposited early in the hypogene mineralization were partly or wholly dissolved at a later stage in the process, and other ore minerals more stable in the presence of the changed solutions were deposited in their place.

Some of the general features of the hypogene mineralization and the principles which they exemplify may first be considered. The Tonopah ores are in the main formed by the replacement of igneous rocks; these rocks are aggregates of many mineral species, some of which are more susceptible to replacement, under a given set of conditions, than others. The effects of the first of the hypogene solutions, the advance wave of mineralization, were the replacement of certain of the wall-rock minerals by other nonmetallic minerals and by pyrite, alterations commonly included under the term "hydrothermal alteration." These changes are now shown in the wall rock bordering the veins and probably were accomplished in the main vein zones themselves, where they have since been obliterated by further changes. They have been carefully studied by Spurr.[1] In the Mizpah trachyte, the predominant wall rock of many of the veins, the first alterations commonly consisted in the selective replacement of certain minerals by calcite, siderite, chlorite, sericite, and pyrite; later there was progressive destruction of chlorite and calcite and to some extent of pyrite, accompanied by an increase in the amount of siderite and sericite and the development of quartz and adularia; finally the pyrite was completely redissolved and the rock converted into an aggregate of quartz and silica. These changes, while broadly a part of the mineralization process, preceded the introduction of the valuable metals, for, according to Spurr,[2] the pyritized wall rocks carry only negligible amounts of gold and silver. The present paper is concerned with the succeeding changes, which involved the further replacement of the altered rocks and the development of the typical ore minerals. Mainly for convenience in description and without attributing any particular significance to such a classification, the writers have divided the hypogene ore minerals into two classes—alpha hypogene and beta hypogene.

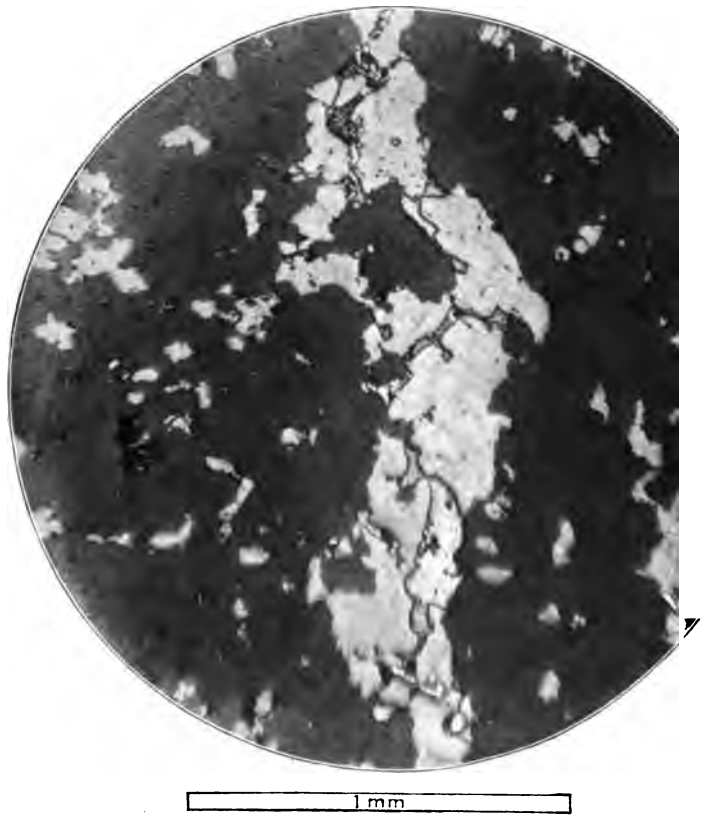
The alpha hypogene minerals are those which are formed by the direct hypogene replacement of wall-rock minerals or their common hydrothermal alteration products, such as sericite and quartz, or which are not demon-

[1] Spurr, J. E., Geology of the Tonopah mining district, Nev.: U. S. Geol. Survey Prof. Paper 42, pp. 207-252, 1905.
[2] Idem, p. 207.



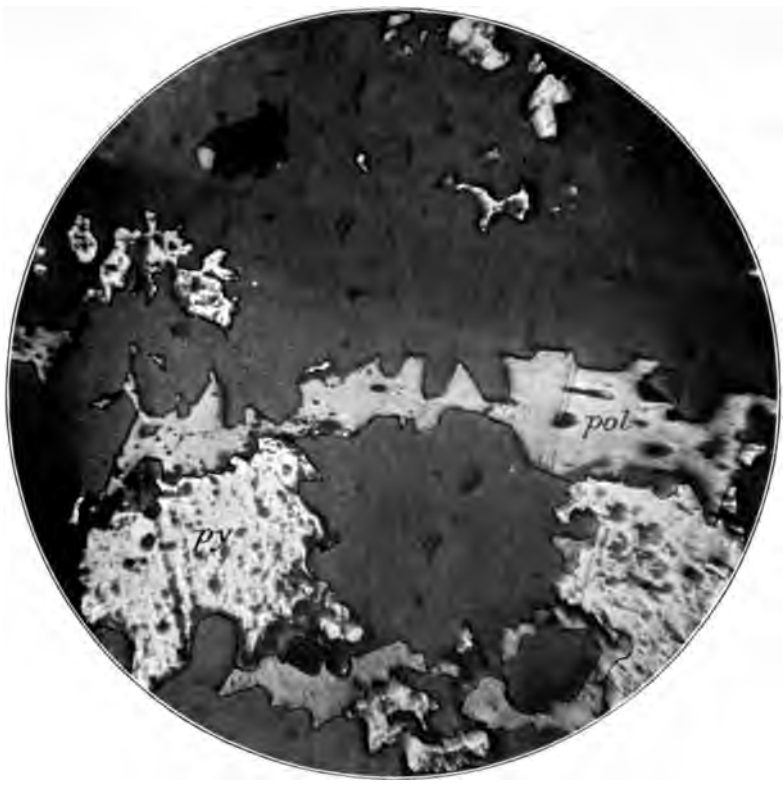
A. HYPOGENE (?) INTERGROWTH OF QUARTZ (DARK) AND PYRARG

Photomicrograph of polished surface of ore from vein between 400 and 500 foot levels, La minerals are believed to be contemporary results of rock replacement



B. IRREGULAR VEINLET OF SPHALERITE (SMOOTH LIGHT GRAY) AND A LIGHT GRAY), BORDERED BY QUARTZ (DARK GRAY), WITH SCATTERED OF SPHALERITE.

The sphalerite-argentite veinlet is believed to mark a line of easy replacement in the original are interpreted as alpha hypogene. Photomicrograph of polished surface of ore from vein, West End mine.



A. IRREGULAR INTERGROWTH OF POLYBASITE (*pol*), PROBABLY ALPHA HYPOGENE, WITH QUARTZ (*q*) AND PYRITE (*py*).

Photomicrograph of polished surface of ore just above 500-foot level. West End vein, West End mine.

B. POLYBASITE (LIGHT GRAY) WITH BLADELIKE OUTLINES, INCLOSED BY PYRARGYRITE (WHITE).

The dark gray is quartz. The polybasite has been made visible by brief treatment with mercuric chloride solution. Photomicrograph of polished surface of ore, Tonopah Extension mine, exact location uncertain.

strably otherwise. The beta hypogene minerals are formed by the replacement of earlier hypogene metallic ore minerals. Replacement of the host rock may go on until it is practically complete, after which further replacement must involve the destruction of earlier ore minerals. The beta hypogene minerals are obviously younger than those particular alpha hypogene minerals which they replace, but they are not necessarily younger than all alpha hypogene minerals. On the contrary, there is much evidence that direct replacement of the host rock by ore minerals at one place was coincident with replacement of ore minerals by other ore minerals at another place. For this reason the terms "alpha" and "beta" are preferred to terms that carry a time significance, such as "early" and "late."

ALPHA HYPOGENE MINERALS.

GENERAL RELATIONS.

The individual grains of the minerals that are believed to be alpha hypogene interlock irregularly in a fashion indicative of mutual interference during growth and produce ore textures somewhat comparable to the granular textures of certain igneous rocks. Typical examples of these textures are shown in figures 3 to 5 and in Plates V, *A*, and VI, *B*. Such textures are indicative of general contemporaneity of the minerals present, although certain minor age differences probably exist, such as are shown by the order of crystallization usually recognizable among the components of a massive igneous rock.

The minerals named below appear to have been formed by alpha hypogene crystallization in nearly all the veins studied—Belmont, Favorite, Shaft, MacDonald, North Star footwall vein, Last Chance, West End, Extension combined vein on 770-foot level, Egyptian, Extension lower contact vein, McNamara, and Murray:

Sphalerite.	Argyrodite (?).
Galena.	Polybasite.
Chalcopyrite.	Argentite.
Pyrite.	Electrum.
Arsenopyrite (noted only in the Last Chance vein).	Quartz.
Pyrargyrite.	Carbonates.

Carbonates were noted in all these veins, but their composition commonly differs from point to point even within a single vein, as explained in the paragraph on carbonates.

SPHALERITE.

Sphalerite, which is one of the commonest sulphides of the ores, was noted only as an alpha hypogene mineral. Crystal faces on sphalerite were noted only in a few places where the mineral was in contact with galena or chalcopyrite. Commonly it forms rounded areas, which are surrounded (see fig. 4) by one or more of the minerals galena, argentite, or chalcopyrite. Such rounded outlines might suggest that the sphalerite has been partly replaced by the minerals that surround it, but there are no other indications that sphalerite has been replaced to more than a very minor extent during the entire process of mineralization. Locally, as shown in Plate III, *B*, the sphalerite has very irregular outlines. This plate also illustrates a less common mode of occurrence of sphalerite, as small, irregular veinlets that appear to have been formed by replacement of the host rock along minute

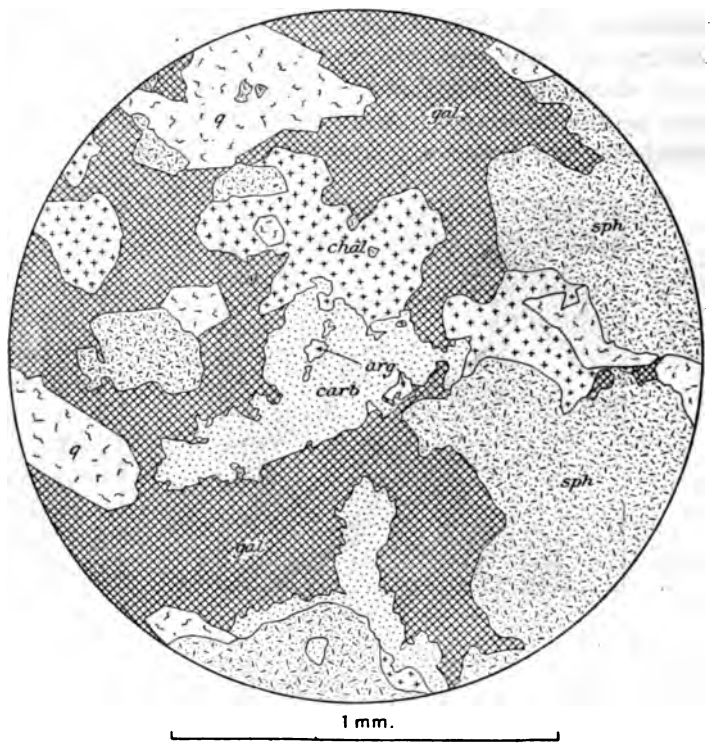


FIGURE 3.—Typical association of alpha hypogene ore minerals. A few small areas of argentite (*arg*) may be later replacement deposits, but the other minerals are believed to be essentially contemporaneous. *q*, Quartz; *gal*, galena; *chal*, chalcopyrite; *sph*, sphalerite; *carb*, carbonate; *arg*, argentite. Camera lucida drawing from polished surface of ore from Favorite vein, Tonopah Belmont mine. Depth uncertain.

fractures. The boundaries between sphalerite and quartz are generally very irregular (see fig. 5) and suggest complete contemporaneity of deposition. In a few places sphalerite is traversed by minute replacement veinlets of chalcopyrite and polybasite, as is shown in Plate VIII, *A*, and figure 7.

In general the maximum deposition of sphalerite and quartz appears to have occurred early in the hypogene mineralization, and the maximum deposition of galena, chalcopyrite, pyrargyrite, and argentite was slightly later, as is shown by their matrical position. The two periods overlapped, however, and locally sphalerite and quartz are later than the other

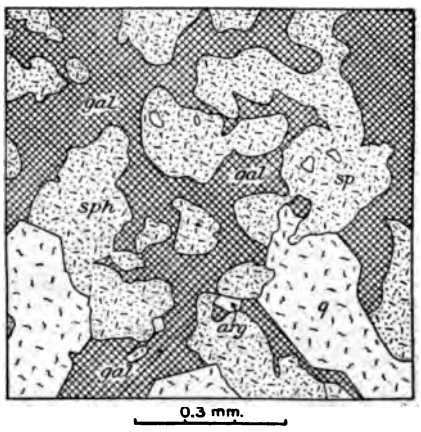


FIGURE 4.—Sphalerite (*sph*) with rounded outlines surrounded by galena (*gal*). A few small areas of argentite (*arg*). *q*, Quartz. Camera lucida drawing from polished surface of ore from Favorite vein, Tonopah Belmont mine. Depth uncertain.

minerals. In most of the ores sphalerite is not identifiable without the aid of the microscope.

GALENA.

Galena, which is also one of the commonest sulphides of the ores, was noted only as an alpha hypogene mineral. It almost invariably conforms to the crystal outlines of bordering quartz areas, as shown in figure 3, and in many places it forms the matrix of areas of sphalerite of rounded outline, as shown in figure 4. Its contacts with alpha hypogene chalcopyrite and argentite are commonly irregular or smoothly curving. Galena has been replaced by beta hypogene minerals to a greater extent than any other sulphide.

CHALCOPYRITE.

Alpha hypogene chalcopyrite is nearly as abundant as sphalerite or galena. It also occurs as a beta hypogene and probably as a supergene mineral, and it is not always possible to determine to which class a given occurrence belongs. Chalcopyrite in relations like those shown in figure 3 is interpreted as alpha hypogene. The mineral commonly conforms to the crystal outlines of quartz and locally embeds sphalerite of rounded or crystal outline. Its boundaries against galena and alpha hypogene argentite are commonly irregular or rounding. Alpha hypogene chalcopyrite has locally been replaced by beta hypogene minerals and by supergene minerals.

PYRITE.

Pyrite is in general less abundant in the ores than chalcopyrite, but tends to form larger grains. It was the first sulphide to form in the process of mineralization by replacement, and in slightly mineralized rock it is the only one present. (See Pl. XV, *B*.) Its deposition appears to have continued throughout the hypogene mineralization, for in many places it conforms to the crystalline outlines of quartz and has irregular boundaries next to chalcopyrite.

Pyrite appears to have formed locally as a late deposit in open fractures but was nowhere noted as having replaced other metallic ore minerals.

ARSENOPYRITE.

A mineral that is nearly white in the polished sections and only slightly softer than pyrite, though it takes a smoother polish, is probably arsenopyrite. The outlines of the crystal indicate orthorhombic crystallization. Stellar trillings, such as are common in arsenopyrite, were noted. Though the mineral is fairly abundant in an ore specimen from a depth of about 500 feet in the Last Chance vein, it was not noted in any other specimens. It is irregularly intercrystallized with sphalerite, galena, and quartz, and except for its presence the ore in which it is found presents no unusual features.

ARSENICAL PYRARGYRITE.

Arsenical pyrargyrite, though rare compared with the sulphides of the base metals, is present in all the veins studied and is locally very abundant. Spurr [1] appears to have regarded it as invariably supergene. Some of the pyrargyrite almost certainly is of supergene deposition,

[1] Spurr, J. E., Geology of the Tonopah mining district, Nev.: U. S. Geol. Survey Prof. Paper 42, pp. 94-95. 1905.

as will be shown later, but most of it appears to be hypogene.

Where particularly abundant its chief associates are quartz, polybasite, and probably argyrodite, but in places, as shown in figure 5, it is irregularly intercrystallized with the common sulphides, sphalerite, pyrite, chalcopyrite, etc. Veinlets of pyrargyrite that may be alpha hypogene are described on page 11 and illustrated in Plate II. More irregular intergrowths with quartz of the type shown in Plate III, *A*, were noted in ores from the Last Chance and Fraction veins and the Tonopah Extension mine. A texture of this sort might be explained through the deposition of pyrargyrite in the open spaces of a porous mass of finely crystalline quartz, but it is more probably the result of simultaneous replacement of a rock by quartz and pyrargyrite, for analogous textural relations exist elsewhere between quartz and the commoner sulphides or mixtures of the commoner sulphides with pyrargyrite, as shown in figure 5. In ores like those shown in Plate III, *A*, and figure 5 the quartz possessed greater power of assuming crystal outlines than the other ore minerals. The microscopic intergrowths of quartz and pyrargyrite may constitute several cubic inches of material which, viewed with the unaided eye, appears to be pure pyrargyrite.

FIGURE 5.—Irregular intergrowth of pyrargyrite (*pyrg*) pyrite (*pyr*), and polybasite (*pol*). Camera lucida dr from Fraction vein, Jim Butler mine, between 600 an

A few small crystals of pyrargyrite occur in vugs, and the angles of some of these have been measured by Eakle.[1]

A large number of samples of pyrargyrite heated in closed tubes before the blowpipe carried arsenic, and in some samples arsenic appeared to be as abundant as antimony.

Pyrargyrite was not noted as replacing other ore minerals (beta hypogene).

Louis G. Ravicz [2] in a recent paper expresses the view that the sulphosalts of silver, such as pyrargyrite and polybasite, can not be formed by precipitation from solutions containing alkaline sulphides through decrease of pressure or temperature alone, because under ordinary pressures they are unst alkaline sulphides. He ever these minerals ar primary occurrences t resulted from the mingli sulphide solutions with tions. It appears to improbable that oxidati any significant amount when hot mineralizing ascending. Unless it is deposits from hypogene being formed at the p supposed that certain l even the majority) are of mineralization in Mineral deposits being surface in regions of h characteristically rich i metallic minerals; m minerals are confined t as stibnite and cinnab as the writers are aw mon sulphides galena, copyrite, which are the at Tonopah and are l temporaneously with silver. The compositio formed at the surface a not the most favorable through oxidation of l solutions, even if the u waters did not inhibit

[1] Eakle, A. S., The minerals of Tonopah, Nev.: California Univ. Dept. Geology Bull., vol. 7, p. 9, 1912.

[2] Experiments in the enrichment of silver ores: Econ. Geology, vol. 10, p. 375, 1915.

Furthermore, the mineralogy of the Tonopah ores is not that of the shallowest types of ore deposits. Mining has shown that the hypogene ores range through a vertical interval of 1,500 feet without notable change in mineral composition, and it seems probable that they were originally deposited at several times this depth, at horizons where effective mingling with acid supergene solutions probably could not occur. If Ransome [1] has correctly interpreted the formation of alunite at the neighboring camp of Goldfield as the result of a mingling of descending acid solutions with the ascending solutions, the absence of alunite at Tonopah may be taken as additional evidence that such intermingling did not take place there.

Although the writers are not inclined to regard the mingling of supergene with hypogene solutions as the cause of the precipitation of the hypogene sulphosalts of silver at Tonopah, these minerals are in the main the latest of the hypogene minerals, and it is quite probable that at the time they were deposited the hypogene solutions had become somewhat depleted in alkalies, through sericitization of the wall rocks, and in sulphur, through precipitation of the early hypogene sulphides.

ARGYRODITE (?).

In intergrowths of quartz and pyrargyrite, such as those shown in Plate III, *A*, small amounts of polybasite occur, and also a metallic mineral that could not be certainly identified. This mineral, which is irregularly intergrown with the pyrargyrite and polybasite and is plainly contemporaneous with them, is recognizable only upon microscopic study of polished specimens. On freshly polished surfaces it is distinguishable from the pyrargyrite, though not easily, by its slightly pinkish tint. It is brittle and near pyrargyrite in hardness, but has a black streak about like that of polybasite. It is not tarnished by silver nitrate or mercuric chloride solutions that tarnish pyrargyrite and polybasite brown. The mineral was found in too small amounts to be isolated for analysis, but its physical properties appeared to agree with those of the mineral argyrodite (Ag_8GeS_6 or Ag_6GeS_5), in which the element germanium was first discovered. Chase Palmer, of this Survey, has made careful qualitative tests for germanium in a sample of the mixture which carried the unknown mineral and definitely determined that this element was present. It is therefore probable that the mineral argyrodite is present in these ores, although the possibility that the germanium may be in some other mineral combination can not be excluded.

In the two localities in which argyrodite has been identified, it is also associated with other silver minerals. Near Freiberg, Saxony, it is associated with pyrargyrite, polybasite, stephanite, and common sulphides of the base metals.[2] In Bolivia it is associated with polybasite and stephanite.

POLYBASITE.

The mode of occurrence of polybasite is very similar to that of pyrargyrite, with which it is commonly associated. It occurs not only as an alpha hypogene but also as a beta hypogene and a supergene deposit. In its alpha hypogene occurrence it may be irregularly intergrown with pyrargyrite and the commoner sulphides, as shown in figure 5, or may be a component of veinlets of the type illustrated in Plate II, *A* and *B*. In a few deposits of the type shown in Plate IV, *A*, the polybasite, probably hypogene, is intimately intercrystallized with quartz and pyrite.

In one specimen from the Tonopah Extension mine polybasite inclosed by pyrargyrite showed the blade-like forms illustrated in Plate IV, *B*. These blades are presumably cross sections of polybasite crystals.

STEPHANITE (?).

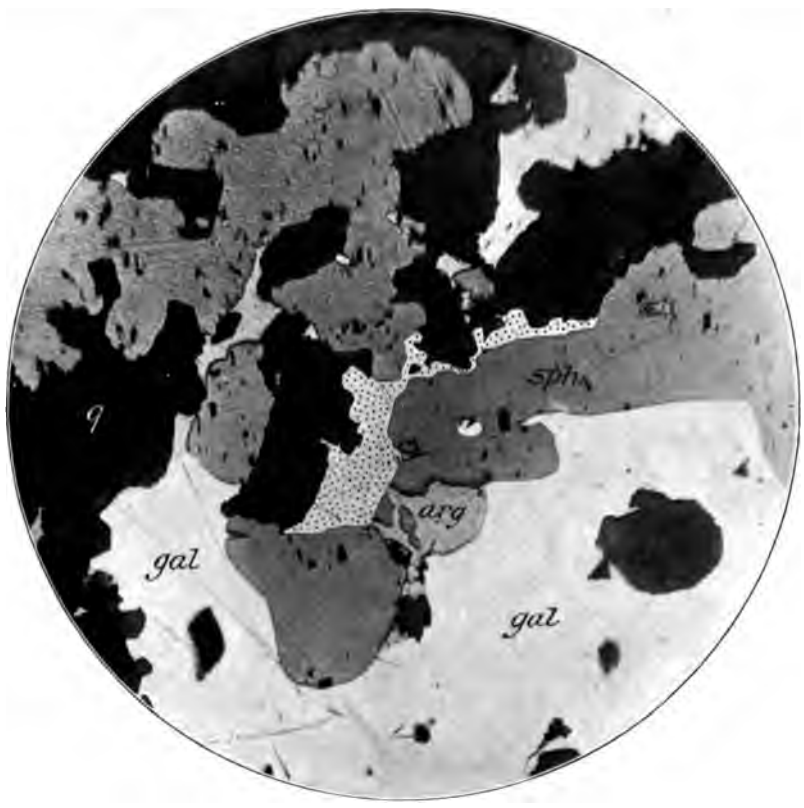
The presence of stephanite in the Tonopah ores has not been proved. Numerous tests were made on crystals that from general appearance might be either stephanite or polybasite, to determine whether they contained copper. Upon dissolving in nitric acid and neutralizing with ammonia the blue color of the copper-ammonium salt was obtained in every test. This was not due to admixed chalcopyrite, for no precipitate of ferric hydroxide formed. All these crystals were therefore identified as polybasite. Spurr [3] and Eakle [4] also

[1] Ransome, F. L., The geology and ore deposits of Goldfield, Nev.: U. S. Geol. Survey Prof. Paper 66, pp. 193–195, 1909.

[2] See Hintze, Carl, Handbuch der Mineralogie, Band 1, Abt. 1, pp. 1193–1197, 1904, for full references to the literature.

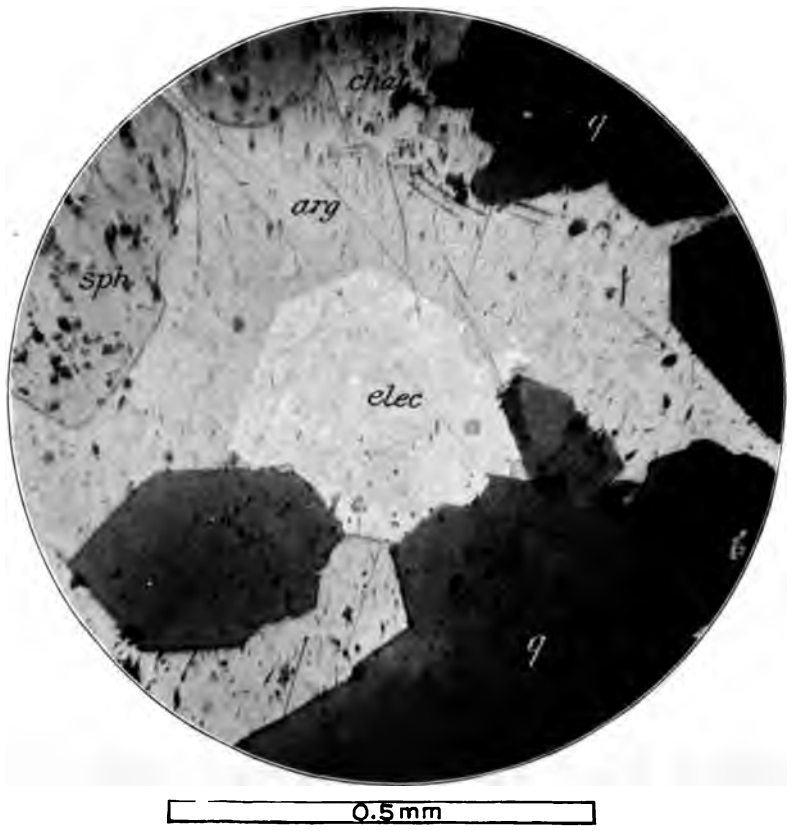
[3] Spurr, J. E., Geology of the Tonopah mining district, Nev.: U. S. Geol. Survey Prof. Paper 42, p. 95, 1905.

[4] Eakle, A. S., op. cit., p. 9.



A. ELECTRUM (STIPPLED) IRREGULARLY INTERGROWN WITH SPHALERITE /

The argentite (*arg*) shown in this photograph was probably formed by the replacement (beta hypoge all the other minerals, including the electrum, are believed to be alpha hypogene. P polished surface of ore from 1,050-foot level, Macdonald vein, North Star mine. *sph*, Sphaleri

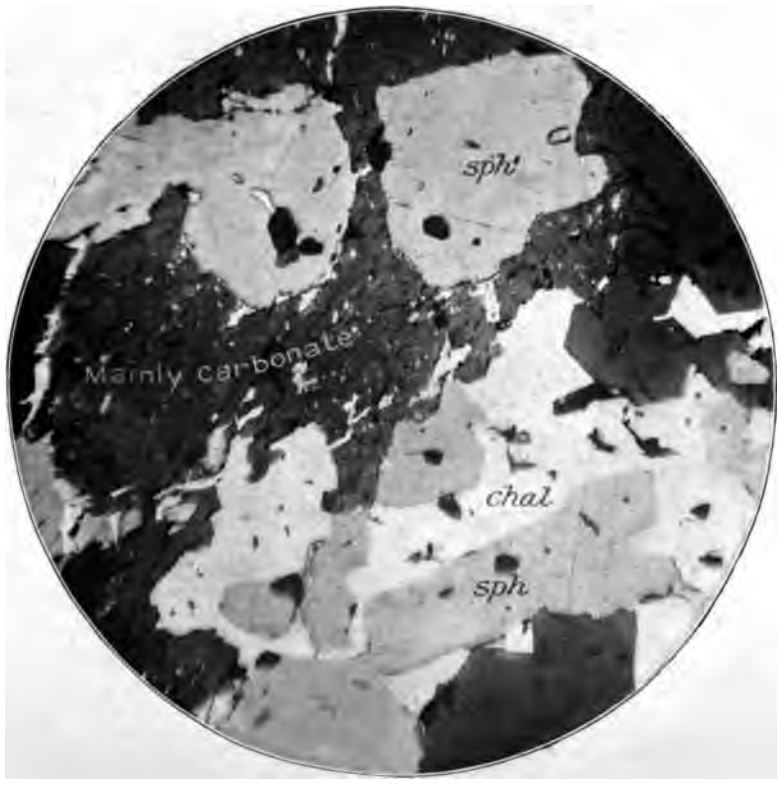


B. ELECTRUM SHOWING CRYSTAL OUTLINES ASSOCIATED WITH QUARTZ AN

The argentite was very probably formed by the replacement of galena, but all the other mineral alpha hypogene. Photomicrograph of polished surface of ore from 1,260-foot level, Mur Extension mine. *chal*, Chalcopyrite; *sph*, sphalerite; *arg*, argentite; *elec*, electrum; *q*, quartz.

ADIATING INTERGROWTHS OF QUARTZ (WHITE) AND FERRUGINOUS RHODOCHROSITE (GRAY) WITH SMALL PATCHES OF FINELY DIVIDED SULPHIDES (BLACK).

nicrograph (ordinary light) of thin section of ore from 1,000-foot level, Belmont vein, Tonopah-Belmont mine.



REGULAR FINE AGGREGATES OF CARBONATE, ARGENTITE, AND CHALCOPYRITE (*chal*) INTERGROWN WITH ORE MINERALS IN LARGER GRAINS.

nicrograph of polished surface of ore from Favorite vein, Tonopah-Belmont mine. *sph*, Sphalerite; *q*, quartz.

were unable to identify any of the "brittle silver" as stephanite.

ELECTRUM.

A pale-yellow mineral that is sectile and is not tarnished by HCl, HNO_3, or $(NH_4)_2S$ is recognizable under the microscope in a large number of the ores. It occurs in grains so fine that its mechanical separation from the other ore minerals is extremely difficult. Ore from the West End vein between the 400 and 500 foot levels that was known from microscopic study to carry this mineral was very finely crushed and carefully panned. After the heavy pannings were treated with hot dilute nitric acid to dissolve the sulphides, numerous heavy minute black particles, visible under a hand lens, remained. Upon further treatment with hot concentrated nitric acid these particles acquired the yellow color characteristic of gold. Similar blackening of the mineral upon treatment with dilute acid was also noted by Hillebrand. Several specimens shown by microscopic study to be rich in the light-yellow mineral assayed exceptionally high in gold. This mineral is believed to be electrum, possibly carrying some selenium, as discussed below. This conclusion accords with the studies of Hillebrand on ores collected by Spurr, which showed that at least some of the gold in the ores was heavily alloyed with silver.

A number of assays of Tonopah ores exceptionally rich in gold are given below. How much of the silver in these ores was alloyed with gold is unknown, for sulphides and sulphosalts of silver were present in all the samples.

Assays of some Tonopah ores.

[Ounces per ton.]

	Gold.	Silver.
1. North Star mine footwall vein, 1,250-foot level; grab sample from 250 tons	47.96	19.35
2. Same locality as No. 1; picked piece of rich ore	367.22	185.15
3. Same locality as No. 1; two pieces	79.60	36.20
4. Same vein as No. 1, stope above 1,130-foot level	10.72	681.90
5. West End vein in stope 522 between 500 and 600 foot levels; small piece of rich ore	23.50	1,483.00

Assays 1 to 4 above were communicated by Mr. A. E. Lowe, superintendent at the North Star mine. Sample 2 is said to have shown no free gold, even on panning; presumably the gold was in very minute grains, which were not freed from the sulphides in the crushing preparatory to panning. Microscopic examination by the writers of ore said to be from the lot represented in assay 4 revealed the presence of the light-yellow sectile mineral in unusual abundance and in unusually large grains (as much as 0.36 millimeter in diameter). A part of the silver in this ore occurs in pyrargyrite, polybasite, and argentite, all of which were identified microscopically. Assay 5 was made by the Bureau of Mines on a small sample collected by the writers and shown by microscopic study to be unusually rich in the light-yellow mineral. Pyrargyrite, argentite, and polybasite were also recognized microscopically in this sample.

In most of the ores the electrum grains conform to the characteristic rounded boundaries of sphalerite and to crystal boundaries of quartz, sharing the matrical position of galena, chalcopyrite, and argentite. (See Pl. V, *A*.) In places it develops crystal faces. (See Pl. V, *B*.) The argentite shown in Plate V, *B*, is believed to have been formed, at least in part, by the replacement of galena, for reasons discussed in the section on argentite (p. 18). It is possible that the electrum in this section also replaces galena, but more probably it crystallized contemporaneously with the galena whose place is now occupied by argentite. Exceptionally the electrum is intercrystallized irregularly with sphalerite or bordered by it on all sides in the plane of the section. In a number of ores it was observed as a minor component of the carbonate-sulphide aggregates. (See p. 18 and Pls. VI, *B*, and VII, *A*.)

SELENIUM.

Small amounts of selenium have long been known to be present in the ores of Tonopah and in the derived concentrates and bullion. The largest amount recorded is 2.56 per cent, in an analysis by W. F. Hillebrand of pannings from heavy sulphide ore (analysis 2, p. 46). The mineral combination in which it occurs is not yet definitely determined, but there is consid-

erable ground for believing that it is associated with the gold and silver in electrum. Mr. Palmer definitely determined the presence of selenium in pannings consisting mainly of electrum, from ore obtained in the West End mine; unfortunately the quantity of material available was very small. It is possible that selenium produced the blackening in the electrum upon treatment with dilute nitric acid, noted above.

ARGENTITE.

The extent to which argentite occurs as an alpha hypogene mineral is somewhat uncertain. In a few places it is associated with sphalerite in the irregular fashion shown in Plate III, *B*, and in such places it appears to be alpha hypogene. Small areas of argentite bordered on all sides, in the plane of the section, by sphalerite, as shown in figure 4, also appear to be alpha hypogene. Argentite is also an abundant component of the fine carbonate-sulphide intergrowths described below, and in some of these it probably directly replaces the host rock and is therefore alpha hypogene.

One of the commonest modes of occurrence of argentite is shown in figure 10 and Plate V, *B*. In the specimens illustrated its position is interstitial with respect to quartz with crystal outlines and entirely similar to that commonly assumed by galena. (See fig. 4.) As a rule it is possible to prove that this argentite is at least in part formed by the replacement of galena, but some of it may directly replace the host rock.

Argentite is also abundant as a supergene mineral.

QUARTZ.

Quartz is the most abundant gangue mineral of the ores and is universally present. Most of it appears to have been formed by direct replacement of the host rock. In a few places it appears to have been replaced by the carbonate-sulphide aggregates described below, but replacement of quartz has occurred only to a very minor extent in this district.

Thin coatings of quartz, locally found on the walls of certain open fractures, are believed to be in part supergene and in part very late hypogene deposits.

CARBONATES.

The pale-pink material so abundant in many of the Tonopah ores has commonly been termed rhodonite, on account of its apparent hardness, the fact that it effervesced with acid being attributed to admixed carbonates. Microscopic study shows, however, that it is a very fine intergrowth of quartz and a carbonate, and that no rhodonite is present.

An analysis by W. F. Hillebrand [1] of sulphide ore from depths of 460 to 512 feet in the Montana Tonopah mine showed that four elements were combined as carbonates in the following proportions: Calcium 2.7, magnesium 0.9, iron 1.14, and manganese 1.32. Qualitative tests by the writers on pink carbonate from the 906-foot level on the Murray vein showed the presence of calcium, magnesium, manganese, and a very small amount of iron. Carbonate of similar appearance from the 1,260-foot level on the same vein carried a much larger proportion of iron. The fine state of division of the carbonate in the ores makes it difficult to determine whether several hypogene carbonates are present in varying proportions or a single carbonate of varying composition.

Much of the carbonate is present in the fine intergrowths with sulphides, which are described in the next section, but radiating intergrowths with quartz of the type shown in Plate VI, *A*, are common, especially in banded ores like those shown in Plate I.

In some veins, such as the Murray, intergrowths of quartz and pink carbonate are very abundant and give a pink cast to much of the ore; in other veins, such as the West End and Favorite, hypogene carbonates are usually visible only with the aid of the microscope.

Carbonates also occur as supergene deposits.

CARBONATE-SULPHIDE AGGREGATES.

Microscopic aggregates of light-colored carbonates with one or more of the minerals chalcopyrite, galena, argentite, and polybasite are common in many of the ores and are shown in Plate VI, *B*. Usually only one of the silver minerals is present. In general, all the minerals of these aggregates conform to the crystal outlines of quartz and to the rounded outlines of sphalerite. The fine aggregates are, as a rule, sharply demarked from the bordering coarser material, but exceptionally there are gradual transitions from fine aggregates in which carbonates predominate to coarser intergrowths in which sulphides predominate.

[1] Spurr, J. E., Geology of the Tonopah mining district, Nev.: U. S. Geol. Survey Prof. Paper 42, p. 89, 1905.

Such a transition from areas consisting mainly of carbonate with small amounts of galena and argentite to areas consisting of mainly galena and argentite with scattered patches of carbonate is shown in Plate VII, *A*. Transitions into areas consisting mainly of chalcopyrite were noted in other specimens. These transitions, as well as the matrical position of the carbonate-sulphide aggregates, indicate that they were deposited for the most part contemporaneously with the larger areas of galena and chalcopyrite. As already stated, a few grains of electrum occur in some of these aggregates.

WOLFRAMITE.

The tungstate of iron and manganese has been noted at a number of localities in the mines at Tonopah. The writers are not completely informed as to all its occurrences, but it was noted by them in the Belmont vein and in a small vein in the Valley View mine.

In the Valley View mine, on the 300-foot level, quartz and wolframite form a small vein as much as 4 inches wide, lying well within the footwall of the Valley View vein. Its relations to the silver veins are not shown.

In the Belmont vein as exposed on the 1,000-foot level of the Tonopah Belmont mine, in south crosscut 1044, wolframite is very abundant and its relation to the silver ore is well exhibited. The silver ore at this locality consists mainly of quartz and an intergrowth of quartz and ferruginous rhodochrosite of the sort described on page 18, through which aggregates of very finely divided sulphides are distributed. Fractures traversing this ore are partly or completely filled with crystalline quartz, with which wolframite is so intimately intergrown as to leave no doubt that the quartz and wolframite are strictly contemporaneous. Wolframite is also intercrystallized with quartz that lines vugs in quartzose parts of the ore.

So far as the writers are aware wolframite has nowhere been established as a mineral of supergene deposition. The wolframite at Tonopah is believed to have been deposited from ascending silica bearing waters after the deposition of most of the silver ores and after these ores had undergone some fracturing.

BETA HYPOGENE MI

GENERAL FEATU

Certain minerals and mine the Tonopah ores are formed ment of earlier ore minerals direct replacement of the wa products of its hydrothermal criteria by which those depo earlier ore minerals may b these ores are here briefly sur of the deposits are believed and others supergene, and distinguishing between them pages 24 and 42.

The textural relation of th erals of greatest diagnostic

FIGURE 6.—Replacement of galena (*gal*) by contacts with other minerals (as at *A* and *A'* two differently oriented galena crystals (as cleavages (as at *C*). Rims of an earlier those shown in figure 14 are invariably pr and galena but are too narrow to be shown *carb*, carbonate; *chal*, chalcopyrite; *sph*, sp drawing from polished surface of ore from Belmont mine. Depth uncertain.

localization at places that channels of easy access for m tions. Situations particularly replacement of hypogene ore n ore minerals are the following

1. Contacts between hypog different species, at least on replaceable under the then exi In such situations the rep

commonly form narrow replacement bands, as shown at *A* and *A'* in figure 6 and in Plate VIII, *B*.

2. Contacts between two crystals of the same replaceable mineral. The replacing mineral along such contacts commonly takes the form of narrow bands expanding here and there into lenticular areas, as is well shown at *B* in figure 6 and *A* in Plate VII, *B*.

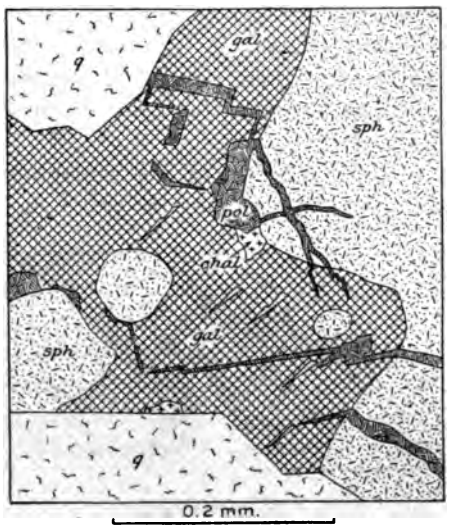


FIGURE 7.—Replacement of galena (*gal*) and sphalerite (*sph*) by polybasite (*pol*) and chalcopyrite (*chal*). In sphalerite the replacement veinlets are commonly irregular, but in galena many of them follow cleavage directions. Locally the replacement has followed the contacts between galena and other minerals. *q*, Quartz. Camera lucida drawing from polished surface of ore from Belmont vein, 1,200-foot level of Tonopah Belmont mine.

3. Narrow wedges of replaceable mineral between converging contacts with other minerals or between intersecting fractures. These are particularly vulnerable to replacement, as is well illustrated at *A* in figure 9.

4. Cleavage planes in replaceable minerals or obscure fractures following cleavages. Replacement of galena along cleavages is shown at *C* in figure 6 and in figure 7.

5. Minute irregular fractures. Replacement along irregular fractures in sphalerite is shown in figure 7 and in Plate VIII, *A*.

The replacement of alpha hypogene minerals appears not to have been confined to situations of obvious vulnerability but in many places seems to have proceeded irregularly through the ore. Some deposits so formed represent merely advanced stages of a process which began by replacement along mineral contacts or fractures, but in reference to others it seems necessary to conclude that the ore was so thoroughly "soaked" with the replacing solutions that replacement proceeded with great facility, without much regard to the earlier textural features of the ore. Instances of replacement of this sort will be cited in the detailed descriptions. In some places the resulting textures can be identified as due to replacement only by local gradations into undoubted replacement deposits along mineral contacts and fractures or by close textural and mineralogic resemblance to such deposits.

The minerals believed to have been formed by hypogene replacement of earlier hypogene ore minerals are polybasite, argentite, an undetermined mineral that is probably a lead-silver sulphide, chalcopyrite, electrum, and a fine-grained carbonate-sulphide aggregate.

POLYBASITE.

Polybasite is very common in the ores of Tonopah, replacing galena and, very rarely, sphalerite. The situations at which replacement may occur are well shown in figures 6, 7, and 8. Along the contacts between galena

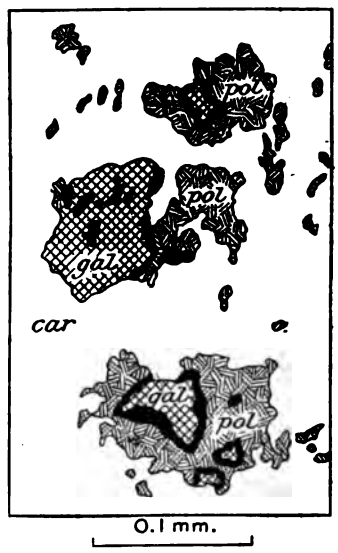
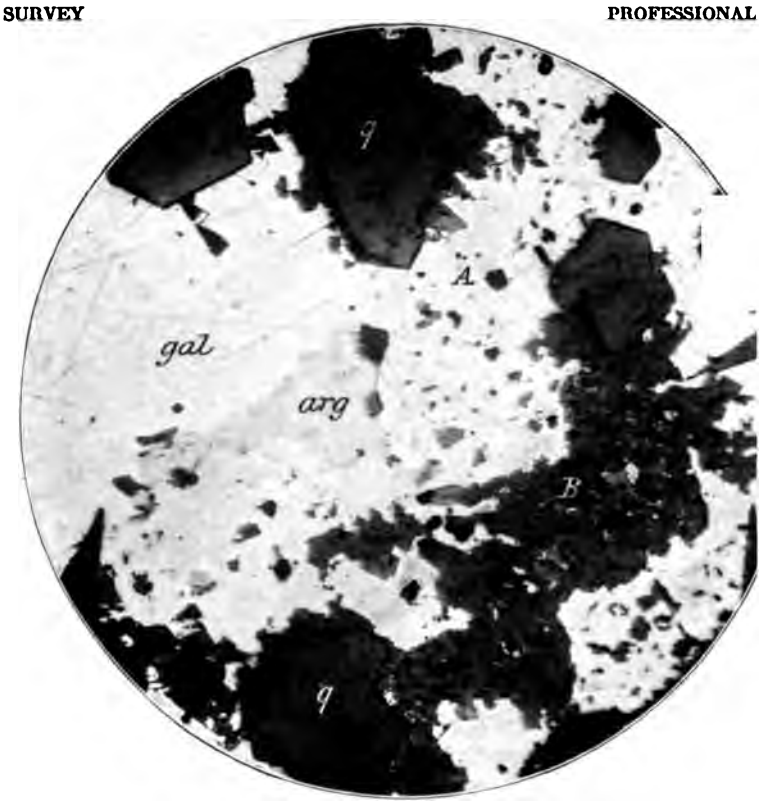


FIGURE 8.—Small areas of galena (*gal*) in the fine carbonate-sulphide aggregates partly replaced by polybasite (*pol*). The first product of the replacement, possibly a lead-bearing silver mineral, forms narrow rims (black in the drawing) between the galena and the polybasite. *car*, Carbonate. Camera lucida drawing from polished surface of ore from Favorite vein, Tonopah Belmont mine. Depth uncertain.

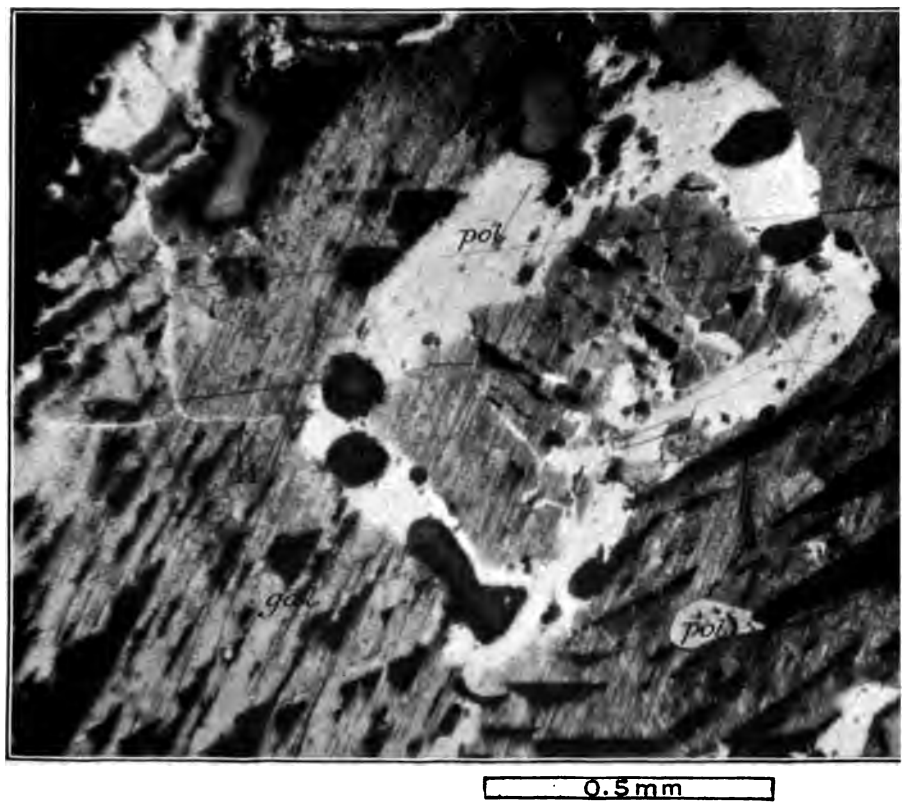
crystals the replacing mineral commonly appears in the polished sections as minute threads (as at *A*, Plate VII, *B*), which enlarge to lenses at intervals (as at *B*, fig. 6).

Very rarely polybasite occurs alone or with chalcopyrite as minute replacement veinlets in



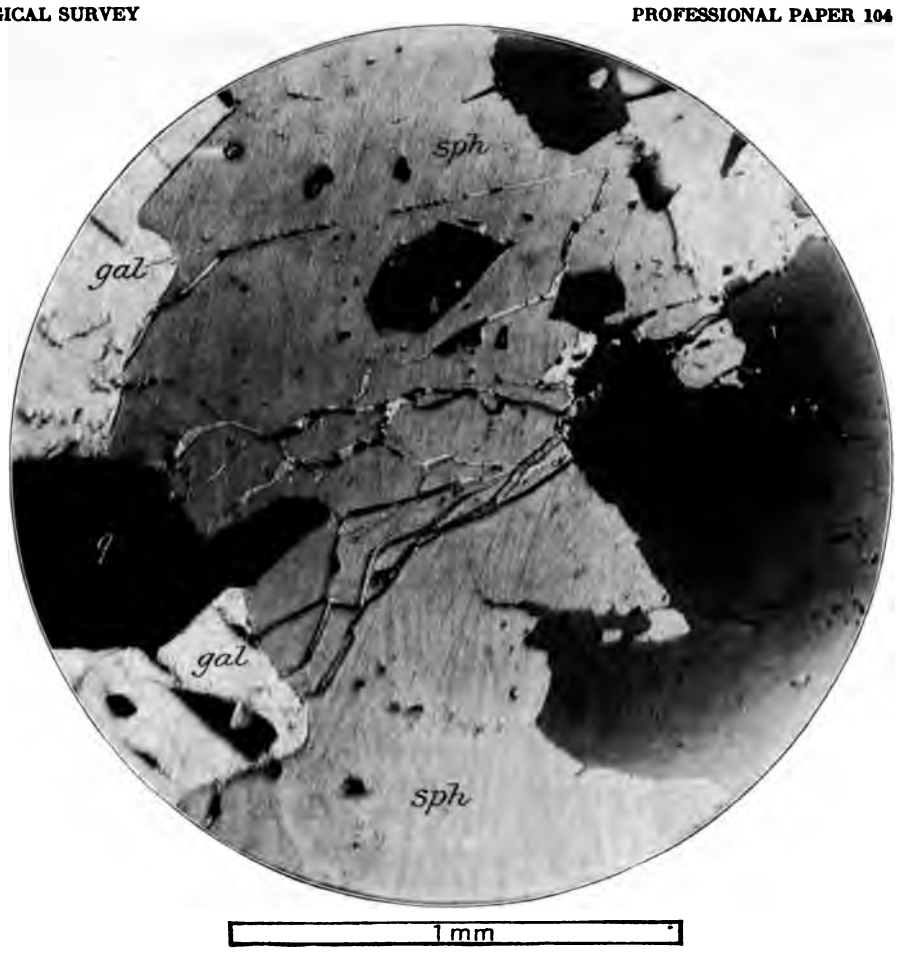
A. TRANSITION FROM AREAS WHOLLY GALENA (*gal*) INTO AREAS (*A*) TI GALENA WITH SOME CARBONATE (ROUGH DARK GRAY) AND ARGENTITE INTO AREAS (*B*) THAT ARE MAINLY CARBONATE WITH SOME ARGENTI COPYRITE, AND ELECTRUM, NAMED IN THE ORDER OF ABUNDANCE.

Photomicrograph of polished surface of ore from 1,000-foot level, Favorite vein, Tonopah-Belı



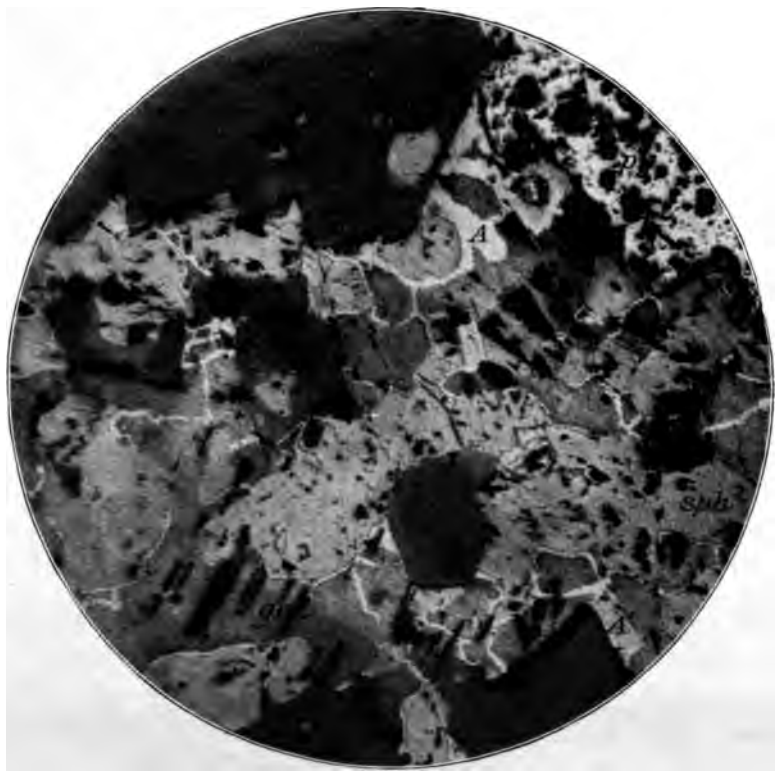
B. REPLACEMENT OF GALENA (*gal*) BY POLYBASITE (*pol*).

Between these two minerals occur narrow bands of an unidentified transition mineral (not visi the very narrow light-colored bands (as at *A*) that mark the initiation of the replacement pı between galena crystals consist of this mineral. Photomicrograph of polished surface of Tonopah-Belmont mine, depth uncertain.



. SPHALERITE (*sph*) TRAVERSED BY MINUTE VEINLETS OF CHALCOPYRITE AND POLYBASITE.

ome of the veinlets in sphalerite are continuous with areas of the same minerals replacing galena (*gal*); this feature does not show in this picture but is illustrated by figure 7, drawn from the same specimen. The veinlets are in the main formed by replacement, though possibly in small part fracture fillings. Photomicrograph of polished surface of ore from hanging-wall branch of Belmont vein, 1,200-foot level, Tonopah-Belmont mine. *q*, Quartz.



. GALENA (*gal*) BORDERED BY AN UNDETERMINED REPLACEMENT MINERAL, PROBABLY A LEAD-BEARING SILVER SULPHIDE.

a a few places, as at *A* and *A'*, the replacement process has proceeded further, with the development of argentite. Photomicrograph of polished surface of ore from Favorite vein, Tonopah-Belmont mine, depth not known. *q*, Quartz; *py*, pyrite; *sph*, sphalerite.

sphalerite, as is shown in Plate VIII, *A*. These veinlets are commonly irregular in the sphalerite, but upon entering neighboring galena grains they conform to the cleavage planes of the galena. These features are shown in figure 7, a drawing, on a larger scale, from a portion of the specimen shown in Plate VIII, *A*.

In places even minute areas of galena in the carbonate-sulphide aggregates (see p. 18) have been partly replaced by polybasite, as is shown in figure 8.

Between galena and the polybasite which has replaced it, but not between sphalerite and polybasite, there is invariably a narrow band of a third mineral which is evidently a temporary transition product in the replacing process. This appears to be the same mineral that is developed between galena and argentite. It is considered more fully below.

ARGENTITE.

Although argentite occurs as a supergene deposit on the walls of open fractures, it has been formed principally by the replacement of galena. For reasons cited on page 24 most such replacement deposits are believed to be hypogene, although in general appearance they are similar to others that are probably supergene. Typical replacement of galena by argentite is shown in figures 9 and 10 and in Plates VIII, *B*, and IX, *B*. Relations like those shown in figure 10, in which argentite embeds quartz and sphalerite, are particularly common, and are in many places demonstrably the result of replacement of galena by argentite. Areas in which argentite without galena embeds quartz and sphalerite may be traced continuously into others like that shown in figure 10, in which both sulphides are present, the argentite replacing the galena, in part peripherally, with the invariable development between argentite and galena of narrow bands of an intermediate replacement product. In a few places argentite, alone or with chalcopyrite, replaces polybasite (probably alpha hypogene), as is shown in figure 11.

UNDETERMINED MINERAL, PROBABLY BEARING SILVER SULPHIDE.

Between galena and argentite or that has replaced it there is invariab of a replacement mineral repres intermediate step in the alteratio transition bands, which are of varyi are particularly well shown in figu also appear in figures 8 and 14 VIII, *B*. Other illustrations of suc ment deposits do not show these cause they are too narrow to appe scale used. They are not formed galena and chalcopyrite that replac

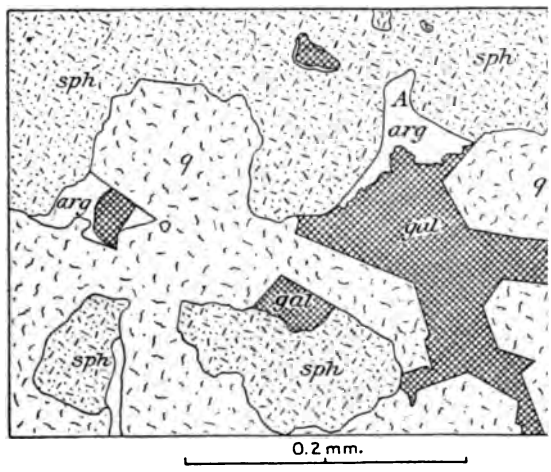


FIGURE 9.—Replacement of galena (*gal*) by argentite (*arg*) at *A*. sphalerite. Camera lucida drawing from polished surface of ore from 1,200-foot level of Tonopah Belmont mine.

the contacts of silver minerals with sulphide save galena.

Here and there the replacement ceeded no further than the format undetermined mineral, as is shown ir Most of the replacement borders Plate VIII, *B*, consist of the unc mineral, but in a few places, as at argentite has formed as the final pr

The transition mineral is indisti from galena on freshly polished su upon treatment with hydrogen pe galena is tarnished brown while the mineral is unaffected. Its hardn by drawing a needle across the galena and the transition minera low power of the microscope, app

about the same as that of galena. The triangular depressions developed in the galena in the grinding process continue into the unidentified mineral, as shown in figures 12 and 14. These depressions are due to the tearing out of small inverted pyramids of the minerals between three intersecting cleavage planes, and their continuity from galena into the other mineral shows that the latter possesses a cleavage identical with and continuous with that of galena. The undetermined mineral is therefore probably, like galena, isometric.

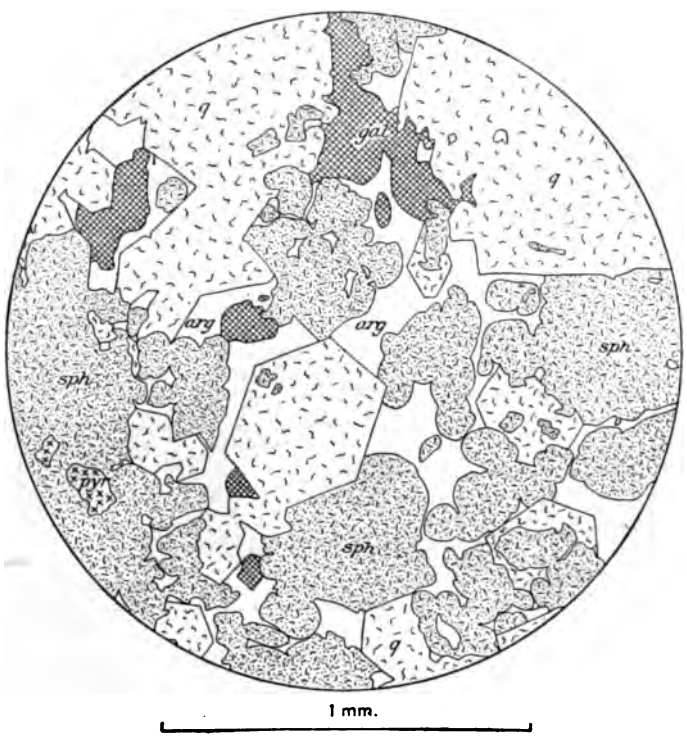


FIGURE 10.—Areas of sphalerite (*sph*) with rounded outlines and of quartz (*q*) with crystal outlines in a matrix consisting mainly of argentite (*arg*). These relations appear to have resulted from the replacement of galena (*gal*, alpha hypogene) by argentite (probably beta hypogene) in ore whose original appearance was like that shown in figure 4. Numerous remnants of galena remain, and between these and the argentite narrow rims of an intermediate replacement product (too narrow to show on this scale) are invariably present. *pyr*, Pyrite. Camera lucida drawing from polished surface of ore from Favorite vein, Tonopah Belmont mine. Depth uncertain.

The mineral is readily distinguished from argentite by its lighter color and the fact that it is brittle rather than sectile. It is present in too small amounts and is too intimately associated with other minerals to be separated for analysis. From the properties already described it is believed to be an isometric mineral with perfect cubical cleavage, in hardness, color, and luster very similar to galena. From its position as a transition product between galena and argentite it may be suspected of being a double sulphide of lead and silver or a solid solution of galena and argentite with physical properties like those of galena.

Chase Palmer, of this Survey, has studied experimentally the action of dilute solutions of silver salts on galena from Joplin, Mo., for the purpose of throwing some light on the character of the transition mineral observed in the Tonopah ores. In his first experiment galena, carefully picked to obtain as pure material as possible, was finely pulverized and treated in a flask with a solution of silver sulphate (about N/40) to which had been added a slightly acid solution of sodium acetate to keep in solution any lead that might be dissolved. The flask was heated in a water bath for two weeks, a stream of purified carbon dioxide passing continuously through it to prevent oxidation by air. At the end of the experiment no metallic silver could be detected by microscopic examination of the solid residue, but it was found that small amounts of lead had been dissolved and some silver removed from the solution.

For a more detailed study of the reaction between galena and a soluble silver salt, Mr. Palmer chose the organic salt silver-benzol sulphonate, which, though resembling the sulphate in containing the SO_3 radicle, is much more soluble and yields a soluble lead salt by reaction with galena. The results are stated by Mr. Palmer[1] as follows:

> The galena, obtained from the Joplin district, Mo., was carefully picked. It was reduced to grains that were collected on a sieve with 40 meshes to the inch. Particles of galena were selected from these small fragments. The mineral thus chosen was ground to pass through a 200-mesh sieve.
>
> *Analysis of the powdered galena.*
>
			Required for PbS.
Lead	86.56	Lead	86.60
Sulphur	13.39	Sulphur	13.40
Iron	Trace.		
	99.95		100.00

[1] Manuscript report, May 16, 1916.

For the experiment, 0.5145 gram of the powdered galena was digested in a solution of silver-benzol sulphonate containing 2.075 grams, slightly acidified with benzol sulphonic acid. The volume of the solution was about 250 cubic centimeters. The mineral was digested in this solution five days on the steam bath. The solution was then filtered. No trace of sulphate was found in the filtered solution, an indication that the sulphur of the galena had not been oxidized.

After the removal of the excess of silver from the solution, it was found that 0.11379 gram of lead had been dissolved. This represents 22.18 per cent of the galena used in the experiment. The residue was found to contain 13.38 per cent of sulphur—that is, all the sulphur present in the galena used—and from the residue was obtained 0.11242 gram of silver, representing 21.85 per cent of the weight of the galena.

$$21.85 \div 107.9 = 0.2025 \text{ silver.}$$
$$22.18 \div 207 \quad 0. = 1071 \text{ lead.}$$

and

$$0.2025 \div 0.1071 = 1.89.$$

The reaction between galena and silver-benzol sulphonate may therefore be written

$$PbS + 2(C_6H_5SO_3Ag) = Ag_2S + (C_6H_5SO_3)_2Pb.$$

The normal reaction occurring between galena and a soluble silver salt may therefore be regarded as strictly metathetical.

Mr. Palmer's experimental results are in agreement with the microscopic evidence in indicating that argentite is one of the stable products of the reaction of a soluble silver salt upon galena. The nature of the intermediate replacement product revealed by the microscope between galena and argentite still remains in doubt; it may be a solid solution of galena and argentite or a double sulphide of lead and silver. Nissen and Hoyt[1] from a study of a series of melts of galena and silver sulphide conclude that "the limit of solid solution at atmospheric temperatures is below 0.2 per cent Ag_2S." The apparent homogeneity of the transition mineral and the extreme sharpness of the boundaries between it and both galena and argentite seem to favor its interpretation as a double sulphide of lead and silver.

Although galena is the mineral most commonly replaced by argentite, a few instances of the replacement of polybasite by argentite or an association of argentite and chalcopyrite were noted, as shown in figure 11.

CHALCOPYRITE.

The copper-iron sulphide chalcopyrite has been formed rather commonly by replacement of galena, either alone or in association with argentite. Where galena has been replaced by a mixture of argentite and chalcopyrite, transition rims of the possible lead-silver sulphide are invariably present between argentite and galena but not between chalcopyrite and galena, a feature which is shown in figure 14. Replacement of polybasite by an association of chalcopyrite and argentite is shown in figure 11. In a very few places chalcopyrite was noted with polybasite in replacement veinlets traversing sphalerite, as is shown in Plate VIII, *A*, and figure 7.

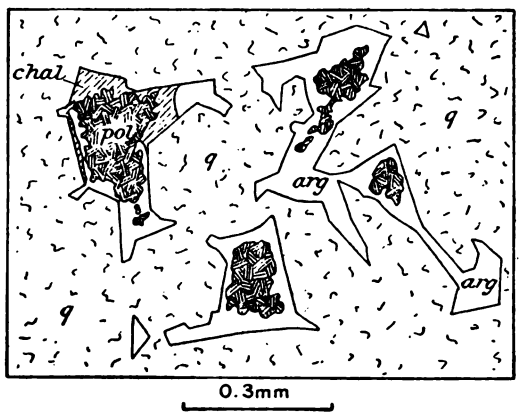


FIGURE 11.—Replacement of polybasite (*pol*), probably alpha hypogene, by argentite (*arg*) and some chalcopyrite (*chal*). *q*, Quartz. Camera lucida drawing from polished surface of ore from Favorite vein, 1,000-foot level of Tonopah Belmont mine.

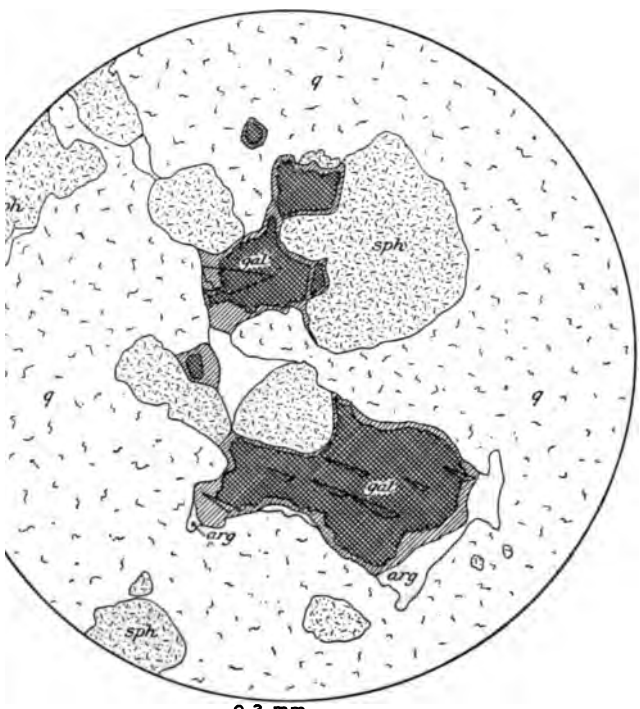
CARBONATE-SULPHIDE AGGREGATES.

Fine aggregates of light-colored carbonate with argentite or polybasite and locally chalcopyrite, identical in character with those described above as probably representing alpha hypogene crystallization, replace galena in a number of the ores. Such replacement is clearly shown in Plate IX, *A*. Carbonate-sulphide aggregates replacing galena occur in the same specimen with aggregates of identical character that apparently have directly replaced the host rock.

Proofs that the aggregates replace galena are found (1) in the minutely irregular character of their contact with galena; (2) in the presence of small "outliers" of galena in the carbonate areas that have the same crystallographic orientation as the larger galena areas near by, of which they were evidently once a part; (3) in the complete transition of carbonate-polybasite

[1] Nissen, A. E., and Hoyt, S. L., On the occurrence of silver in argentiferous galena ores: Econ. Geology, vol. 10, p. 179, 1915.

into areas of polybasite that clearly replace
ı, in the general fashion shown in figure 6;
ł) in the minor irregularity of the contacts
en quartz and the carbonate-sulphide
gates contrasted with the smoothness of
between quartz and galena (a contrast
hown at *A* and *B* in Pl. IX, *A*), indicating



12.—Replacement borders of an undetermined mineral, probably a lead-bearing mineral, around galena (*gal*). The undetermined mineral is in turn replaced by argentite (*arg*). The triangular pits developed in the grinding of the ore are common to the galena and the bordering replacement rims. The surface urnished with hydrogen peroxide to differentiate galena from the undetermineral. *q*, Quartz; *sph*, sphalerite. Camera lucida drawing from polished surore from Shaft vein, 1,000-foot level of Tonopah Belmont mine.

aot galena alone but also small amounts
artz have been replaced by the aggregate.

ELECTRUM.

st of the electrum of the Tonopah ores
urs to replace rock minerals (alpha
gene) directly, as shown in Plate V, *A*
B; some of it is clearly formed by the
cement of galena. In Plate IX, *B*, is
a peripheral replacement of galena by an
iation of electrum and argentite. While
tite and electrum are sharply segregated
fferent parts of the replacement border,
alena boundary shows no jog in passing
the contact with argentite into the contact with galena. Such replacement presents some analogies to the replacement of galena by the carbonate-sulphide aggregates shown in Plate IX, *A*, though in the electrum-bearing deposit only two replacing minerals are involved. Electrum is, indeed, a component of a few such carbonate-sulphide aggregates.

SUMMARY OF EVIDENCE OF HYPOGENE REPLACEMENT.

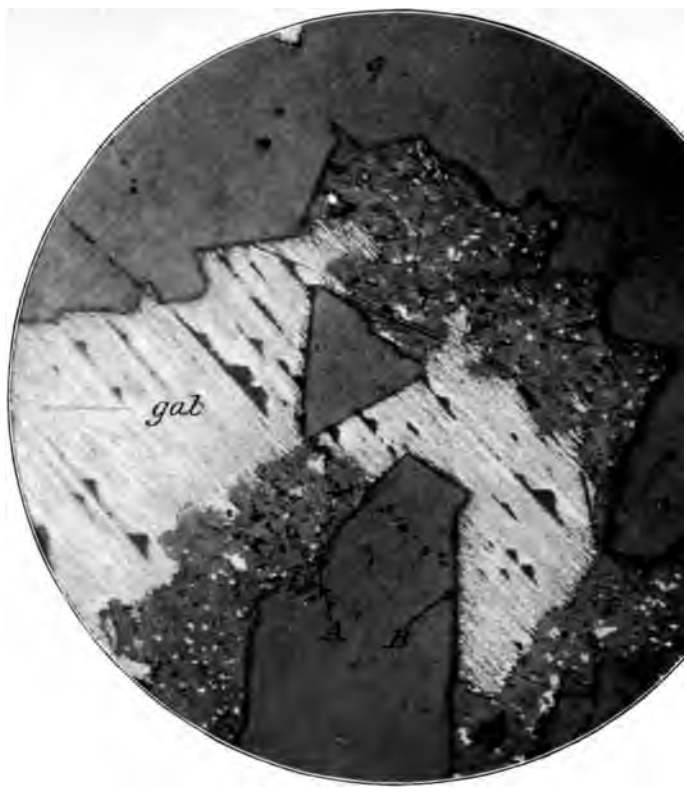
The conclusion that the replacement of one ore mineral by another in the Tonopah ores occurred mainly during the hypogene mineralization is perhaps the most important contribution of this paper. It is therefore desirable to summarize briefly the grounds upon which this conclusion rests.

1. The minerals that are described as formed by hypogene replacement of other ore minerals include no species that are not also found as undoubted alpha hypogene minerals—that is, directly replacing the host rock. The occurrence of electrum of identical appearance intergrown irregularly with sphalerite (alpha hypogene) and also peripherally replacing galena (beta hypogene) is particularly significant.

2. The fine carbonate-sulphide aggregates that replace galena (Pl. IX, *A*) are identical in mineral composition and in texture with others (Pls. VI, *B*, and VII, *A*) that directly replace the host rock and that are irregularly intergrown with coarser and undoubtedly hypogene sulphides.

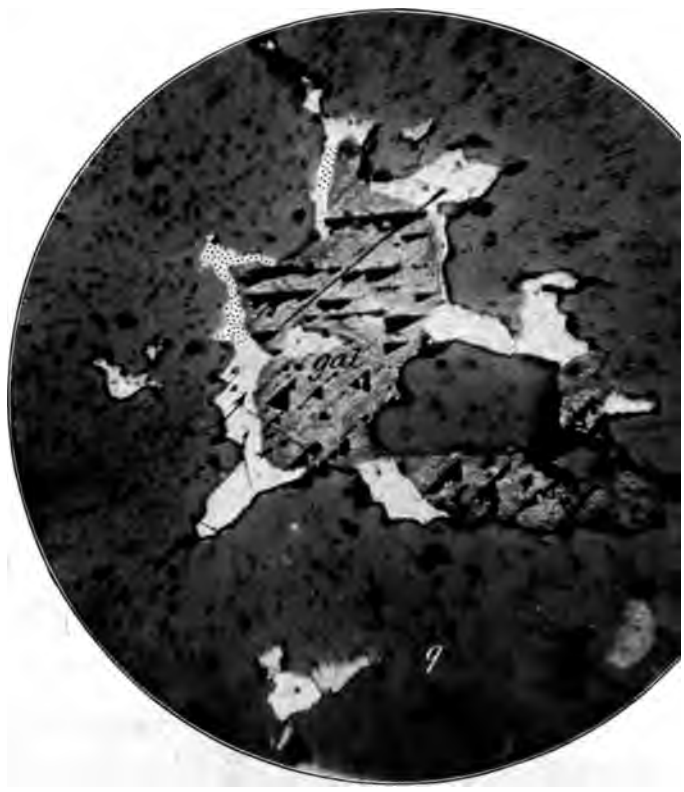
3. Continuous areas of certain minerals and mineral aggregates were noted which appeared at one point to replace the host rock and at another point to replace earlier ore minerals. This was notably true of the carbonate-sulphide aggregates.

4. The presence of electrum peripherally replacing galena is highly suggestive of hypogene origin, for it is well known that gold and silver tend to part company in the processes involved in supergene enrichment because of their great difference in solubility under conditions of oxidation. If the electrum is hypogene the argentite which accom-



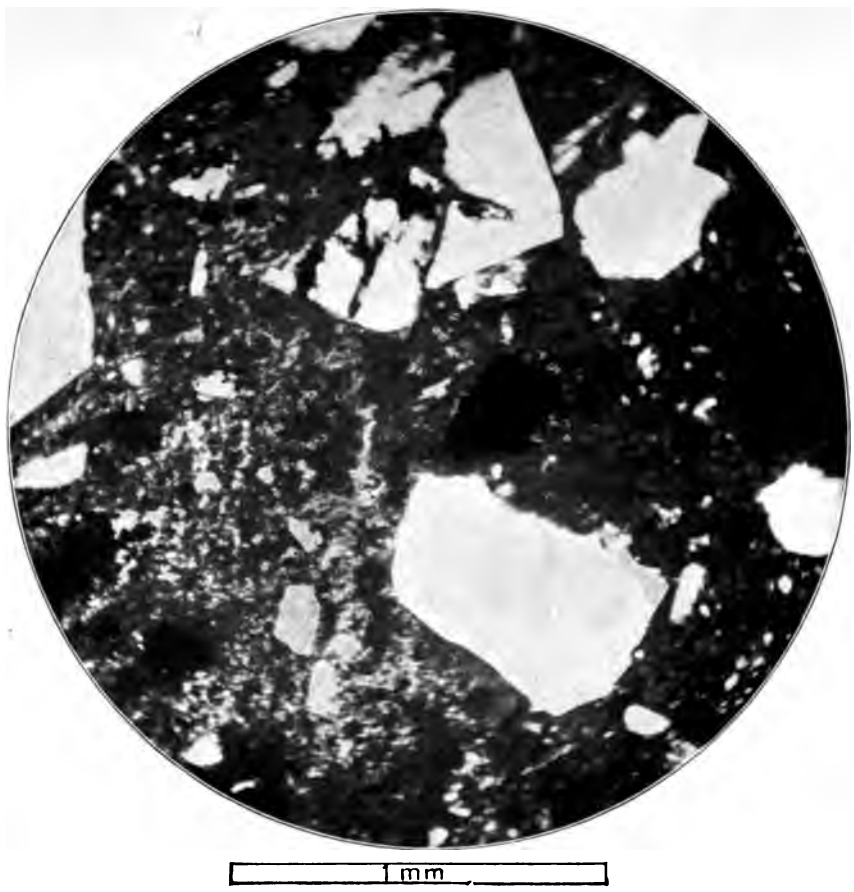
A. PARTIAL REPLACEMENT OF GALENA (*gal*) BY A FINE AGGREGATE OF CARBONATE, ARGENTITE, AND SOME CHALCOPYRITE.

There has also been a slight replacement of the quartz (compare the ragged boundary of th the smooth boundary at *B*). Photomicrograph of polished surface of ore from Favorite mine, depth uncertain.



B. PERIPHERAL REPLACEMENT OF GALENA (*gal*) BY AN ASSOCIATION OF A ELECTRUM (STIPPLED).

Note the smoothness of the galena border in passing from contact with argentite to contac has also been replacement of the type shown in figure 6 along the contact betwee different orientations. Photomicrograph of polished surface of ore from 1,250-foot level Extension mine. *q*, Quartz.



A. PHOTOMICROGRAPH SHOWING TUFFACEOUS CHARACTER OF FRACTION DACITE BRECCIA.

Near station 1447 on 300-foot level of West End mine.

B. FERRUGINOUS CALCITE COATING HIGHLY OXIDIZED ORE JUST BELOW FRACTION DACITE BRECCIA.

From stope 484 not far above 400-foot level, West End vein, West End mine. Two-thirds natural size.

panies it in the peripheral replacement of galena (see Pl. IX, *B*) is also hypogene.

5. Replacement of the type believed to be hypogene is as conspicuous in unoxidized ore from some of the deepest workings (for example, in ore from the 1250-foot level of the Murray vein, Pl. IX, *B;* and from the 1200-foot level of the Belmont vein, figs. 7 and 9) as in ores near the surface. This argument is believed to have weight in spite of the great depth to which oxidation locally extends.

6. The prevalence of the supposed hypogene replacement minerals does not appear to be closely dependent upon the degree of fracturing, as it presumably would if the replacement had been accomplished by supergene solutions. The microscope shows that replacement has been very extensive in ores which exhibit little fracturing and no deposition of supergene minerals along the few fractures that are present.

SEQUENCE IN DEPOSITION AMONG HYPOGENE MINERALS.

The alpha and beta hypogene minerals, which, to simplify the discussion, have been separately described, are believed to have been

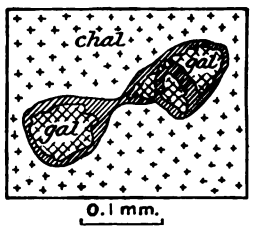


FIGURE 13.—Galena (*gal*) area in chalcopyrite (*chal*) partly replaced by an undetermined mineral, probably a lead-bearing silver mineral. Camera lucida drawing from polished surface of ore from West End vein, between 700 and 800 foot levels of Jim Butler mine.

deposited during a single period of mineralization, in the course of which the composition of the mineralizing solutions gradually changed. In the early stages of the process ore minerals were deposited mainly through replacement of the host rock; later, when less of the host rock remained near the vein fractures and when the character of the mineralizing solutions had changed, certain of the ore minerals, notably galena, were themselves replaced by other ore minerals.

The microscopic relations of the hypogene minerals show that in general quartz and sphalerite were deposited most abundantly early in the mineralization; galena rargyrite, polybasite, arger carbonates of calcium, ma manganese formed most

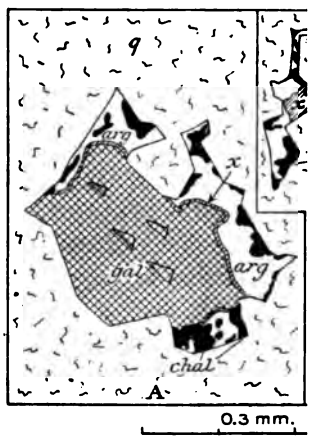


FIGURE 14.—Partial replacement of gale mineral, probably a lead-bearing silver replaced by an association of argentite In the left-hand figure the unidentified band between galena and argentite and and chalcopyrite. *q*, Quartz. Camera surface of ore from West End vein, betv Jim Butler mine.

later in the process. Still some extent sphalerite, qua became unstable and were more of the minerals arge carbonates, and electrum, appears to have persisted r the hypogene mineralizatio

Hypogene replacement o scribed has not been widely dents of ore deposits, becaus scopic study necessary to th been developed only within studies of Rogers[1] and R ores of Butte, Mont., indic replacement has probably process in that district, alt of the mineralization app punctuated by periods of fra extent than at Tonopah.

It appears certain that c in physico-chemical equilib tions either in pressure or the composition of the mi have occurred during the

[1] Rogers, A. F., Upward secondary sul cite formation at Butte, Mont.: Econ. Ge

[2] Ray, J. C., Paragenesis of the ore m Mont.: Econ. Geology, vol. 9, pp. 463–481,

all ore deposits. In ores that are mainly fissure fillings these changes may be recorded by the presence of a suite of minerals in vugs and the medial portions of the veins different from those next the walls, or by crustification in which the layers formed last are mineralogically different from those formed first. In ores formed mainly by replacement such features as those observed at Tonopah may not be present if the earlier minerals are stable in the presence of the later solutions. The writers are inclined to believe, however, that careful study of other ores will show that replacement of earlier ore minerals by later ones during hypogene mineralization is not uncommon.

Although silver minerals and possibly gold were deposited in greatest abundance in the later stages of the hypogene mineralization at Tonopah, the writers prefer not to refer to the process as "upward enrichment," reserving that term for the rare occurrences in which the enriching metals can be shown to have been leached from deeper-lying ore by ascending solutions that were not at the start highly metalliferous. The deeper ores of Tonopah show no evidences of notable solution of any minerals except quartz. In the restricted sense indicated the term may find an application in discussions of certain western deposits in which thermal waters are now ascending along veins. The senior writer has now in hand the study of a number of such deposits.

NATURE OF DEEP MINE WATERS.

Warm waters have been encoutered in a number of the deeper mine workings at Tonopah, particularly in the western part of the camp. The questions arise: Are these waters now depositing ores? If not, what relation, if any, do they bear to the solutions that did deposit the ores?

Water from the Halifax mine, 1,400-foot level, about 380 feet east of the shaft, flowing as a small stream from a fracture in slightly mineralized Mizpah trachyte, had when collected a temperature of 106° F. (41° C.). This water was not acid toward methyl red solution and was not alkaline toward phenolphthalein. It was colorless, clear, and tasteless.

Water from the Tonopah Belmont mine, 1,500-foot level, about 100 feet north of the Belmont vein, had as it issued from the rock a temperature of 99° F. (37° C.). It flowed from drill holes and small fractures in the face of a crosscut and was depositing a sludgy mass of hydrous oxides of iron (ocher-yellow) and oxides of manganese (black). The water as tested in the mine was not acid to methyl red solution and did not appear to be alkaline to phenolphthalein. Field tests with standard potassium permanganate solution showed that practically all the iron was in the ferrous condition. Two gallons of this water was collected and was analyzed by Chase Palmer, of the Geological Survey, with the results shown on page 29.

A sample of water from the Mizpah mine, collected by Spurr, was analyzed by R. C. Wells, of the Geological Survey, in 1910; the results are also recorded in the table. This water flowed from a drill hole which started from the 1,500-foot level of the Mizpah shaft and penetrated 816 feet below that level. Its temperature at the point of issuance was about 106° F.

The analyses are stated in the table in terms of radicles (or the roots of substances), such as Na, Ca, SO_4, and CO_3, which experience has shown to represent basal units of chemical interchange. This method of statement rather than a statement in terms of oxides is particularly appropriate to water analyses, for it indicates the points at which, according to the conceptions of the physical chemist the dissociation of the molecules of dissolved substances occurs. Most substances in water solution are not completely dissociated, the degree of dissociation differing for different substances and varying with temperature, pressure, the concentration of the solution, etc. In general the more dilute the solution the greater the proportion of ionization.

From the mere statement of the analysis in parts per million of the various radicles it is impossible to obtain a clear insight into the quality of the water, because each radicle has a different combining weight. It is convenient, therefore, to divide the total weight of each radicle present by the combining weight of that radicle, to obtain figures representing the reacting values of the radicles. The values so obtained are given in the columns headed "Reacting value by weight" and may be balanced directly one against another by simple addition or subtraction. The 2.205 reacting value of SO_4 in the Belmont water, for example, may be balanced against 3.472 reacting value of Na,

leaving 1.267 (3.472−2.205) reacting value of Na to be balanced against other radicles.

Even this mode of statement is not fully satisfactory when it is desired to compare the qualities of several waters, for the reacting values obtained vary with the concentration of the solution. If the Belmont water, for example, were diluted with an equal volume of pure water the reacting value of each radicle would be halved. It will be readliy understood also that where dilute solutions act through considerable periods of time two waters carrying like constituents in like proportions but differing in concentration will in general produce similar chemical effects but at different rates. Although the concentration of the solution must therefore be duly considered, it is convenient in comparing waters to eliminate this factor. This result may be accomplished by rating the total value of all the radicles as 100 and proportioning the value for each radicle to this total; this has been done in the columns headed "Reacting value by per cent."

The method of statement and interpretation of water analyses here outlined is essentially that developed by Herman Stabler [1] and Chase Palmer,[2] of the United States Geological Survey.

The factors which in general exert the greatest influence on the potency of natural waters as geologic agents are the hydrogen ion and the hydroxyl ion. Hydrogen ions give acidity and hydroxyl ions alkalinity (or basicity); to the physical chemist, indeed, "hydrion" is the true acid and "hydroxion" the true base. Acid and alkaline waters are, at least so far as ore deposition is concerned, the most potent of natural solutions. Hydrogen ions may result from the ionization of free acid present in the water, as they possibly have in the acid water from the West End mine, Tonopah, described on page 43. (See analysis, p. 29.) Hydroxyl ions may result from the ionization of hydroxides present in the water, as in a deep water from the Comstock lode recently analyzed for the senior author by Mr. Palmer. Hydrogen ions may also be liberated less directly by the hydrolysis of various salts and the ionization of the resulting acids; the acidity of copper sulphate in aqueous solution is attributable to this action. Similarly, hydroxyl ions may be liberated by the hydrolysis of various salts and the ionization of the resulting hydroxides; to this action is attributable the alkalinity of a solution of sodium carbonate.

The geologic importance of the presence of so-called free acid or free hydroxides in natural waters is self-evident. The geologic importance of the formation of hydrogen or hydroxyl by hydrolysis and ionization of salts might on first thought be questioned, for the proportion of a salt dissociated at one time is in most cases very small. As soon, however, as the small amounts of hydrogen or hydroxyl formed are neutralized, other hydrogen or hydroxyl ions are at once liberated, and by such progressive action a large part of a salt present in solution may eventually be involved in a reaction. A solution of copper sulphate carrying at any one time only a small proportion of hydrogen ions may, for example, react with calcium carbonate until a large part of the copper is converted into copper carbonate.

The amount of so-called free acid or free alkali present can be computed from the water analysis. At the present stage in the study of water analyses the extent to which hydrogen or hydroxyl ions will be formed through hydrolysis and ionization of salts must be inferred from a consideration of the relative strength of the acids and bases that compose the salts, on the principle that salts of strong acids and weak bases yield an excess of hydrogen ions giving acidity, salts of strong bases and weak acids yield an excess of hydroxyl ions giving alkalinity, and salts of strong bases and strong acids do not hydrolyze perceptibly, and give merely neutrality or salinity in the restricted sense of the term.

The considerations outlined above and the need of reducing so far as practicable the multiplicity of terms in most water analyses make it desirable to group the basic radicles in the general order of the relative strength of their hydroxides and the acid radicles in the general order of the relative strength of their acids or combinations with hydrogen. In the analyses in the accompanying table (p. 29) they are grouped as (1) strong base or alkali radicles, (2) weaker base or alkali-earth radicles, (3) weakest base or metal radicles, (4) strong acid

[1] Stabler, Herman, The mineral analysis of water for industrial purposes and its interpretation by the engineer: Eng. News, vol. 60, p. 356, 1908; The industrial application of water analyses: U. S. Geol. Survey Water-Supply Paper 274, pp. 165–181, 1911.

[2] Palmer, Chase, The geochemical interpretation of water analyses: U. S. Geol. Survey Bull. 479, 1911..

radicles, and (5) weak acid radicles. As the strength of an acid or base is, according to the ionic conception, a direct measure of the degree of ionization [1] such a grouping is a logical preliminary in any attempt to estimate the probable ionization in the solution. By balancing group totals of basic radicles against group totals of acid radicles in accordance with the well-established chemical principle of satisfying the strong acids and bases before the weak, an insight may be obtained into the quality of the water. In some waters individuals within the groups must also be considered. By applying this method of study it is generally possible to determine from the analysis with a fair degree of probability not only whether the water is acid, alkaline, or neutral, but also what constituents have conveyed these qualities to the water. Such computations should be supplemented in the field and in the laboratory by testing the water with indicators. In the present studies methyl red, methyl orange, and phenolphthalein were used in the field.

The details of the method of balancing the radicles are set forth below:

A. Balancing of strong acids.

1. Strong acid radicles should be balanced first against strong base or alkali radicles. Salts derived from strong acids and strong bases do not hydrolyze appreciably in water solution and so impart neither alkalinity nor acidity but merely salinity to the solution.

2. Remaining strong acid radicles should be balanced against alkali-earth radicles. Most salts of the alkali earths and strong acids do not hydrolyze appreciably in water solutions and so impart only salinity to the solution.

3. Remaining strong acid radicles should be balanced against the metallic radicles, the term metallic being here used in the restricted sense, exclusive of the alkali metals and metallic earths. Most of the salts of the metallic elements and strong acids hydrolyze to a considerable degree in water solution. The resulting strong acids ionize to a much greater extent than the weak hydroxides that are also formed, giving an excess of hydrogen ions over hydroxyl ions and rendering the solution acid. Ferric and copper sulphates in water solutions furnish excellent examples of acidity produced in this way. Waters rich in ferric sulphate will vigorously attack iron pipes in mines, even though sufficient iron is already present in solution to balance all the sulphate radicles.[2] The degree of acidity imparted by such salts varies greatly, according to the relative strengths of the acids and bases concerned, so that each association must be individually considered.

4. Remaining strong acid radicles should be considered as in balance with hydrogen radicles—that is, as free strong acid.

B. Balancing of weak acids.

5. Weak acid radicles should be balanced first against alkali radicles if any remain after satisfying the strong acids. Most salts of the alkalies and weak acids hydrolyze to a notable degree in water solution. The resulting alkaline hydroxides ionize to a much greater degree than the weak acids also formed, giving an excess of hydroxyl over hydrogen ions and imparting alkalinity to the solution.

6. Remaining weak acid radicles should be balanced against remaining alkaline-earth radicles. Salts of the alkaline earths and weak acids hydrolyze to some extent in water solutions, yielding hydroxyl ions in excess of hydrogen ions and imparting alkalinity to the water.

7. Remaining weak acid radicles should be balanced against remaining metallic radicles (exclusive of the alkali or alkali-earth metals). The acids and hydroxides resulting from the hydrolysis of these salts are both weak; their ionization being slight, its effect is not likely to be pronounced in the direction of either acidity or alkalinity.

8. Remaining weak acid radicles should be considered as in balance with hydrogen radicles—that is, as free weak acid.

In practice there are always analytical errors that require adjustment in calculations of this sort. If the basic radicles are in excess the reacting values of all of them may be reduced proportionately until their total exactly equals that of the reacting values of the acid radicles. If the acid radicles are in excess and the water is not acid to indicators there has probably been an error in their determination, and the reacting values of all of them may be reduced proportionately until their total exactly equals that of the reacting values of the basic radicles. If the water is acid to indicators, a notable excess of acid over basic radicles is usually interpreted as indicating the presence of free acid; a slight excess is not significant, as the observed acidity may be due to hydrolysis and ionization of salts of strong acids and weak bases. If it is known that the analytical error probably lies in the determination of certain radicles it may be desirable to apply the correction to those radicles only.

[1] Walker, James, Introduction to physical chemistry, p. 313, 1913.

[2] Jones, L. J. W., Ferric sulphate in mine waters, and its action on metals: Colorado Sci. Soc. Proc., vol. 6, pp. 46–55, 1897.

Analyses of mine waters from Tonopah, Nev.

Radicles.	Belmont, 1,500-foot level; temperature, 99° F.; Chase Palmer, analyst.			Mizpah, 2,316-foot drill hole; temperature, near 106° F.; R. C. Wells, analyst.			West End, 500-foot level; acid; Chase Palmer, analyst.		
	Parts per million.	Reacting value by weight.	Reacting value by per cent.[a]	Parts per million.	Reacting value by weight.	Reacting value by per cent.[b]	Parts per million.	Reacting value by weight.	Reacting value by per cent.[c]
Na	80	3.472	31.4	148.8	6.473	30.2	135	5.859	12.7
K	5	.128	1.2	3.4	.087	.4	12	.307	.7
Total alkali radicles			32.6			30.6			13.4
Ca	20	1.000	9.1	68.8	3.433	16.0	249	12.450	27.1
Mg	4.4	.362	3.3	6.3	.518	2.4	10	.822	1.8
Total alkali earth radicles			12.4			18.6			28.9
Fe (ferrous)	3	.107	1.0	.7	.025	.1	7	.252	.5
Al				.7	.077	.4	3	.332	.7
Mn (bivalvent)	[d] 12	.436	4.0				75	2.720	5.9
Zn				Trace.					
(H)									(.6)
Total metal radicles			5.0			.5			7.1
(Deficit of basic radicles)						(.3)			
SO_4	106	2.205	20.2	327.2	6.806	31.7	1,019	21.195	46.0
Cl	35	.987	9.0	35.6	1.004	4.7[e]	65	1.833	4.0
Br and I				None.			[e]		
NO_3				Trace.			None.		
Total strong acid radicles			29.2			36.4			50.0
CO_3	36	1.199	10.9	10.6	.353	1.6	None.		
AsO_4							Trace.		
HCO_3	51	.836	7.6	157.2	2.578	12.0	None.		
Total weak acid radicles			18.5			13.6			
SiO_2	15			64.8			15		
(Deficit of acid radicles)			(2.3)						
Total solids	367.4			824.1			1,590		
		10.732	97.7		21.354	99.7		45.770	99.4
		(f 11.010)	(100.0)		(g 21.482)	(100.0)		(g 46.056)	(100.0)

[a] The reacting values of the basic radicles in this analysis exceed those of the acid radicles but the discrepancy is within the permissible limit of experimental error.
[b] In this analysis the reacting values of the acid radicles exceed those of the basic radicles by a very slight margin, well within the permissible limits of experimental error.
[c] This water was found by testing in the field to be notably acid toward methyl red. The slight excess of acid radicles in the analysis is within the permissible limits of experimental error and is not therefore a certain indication of the presence of free acid. It is uncertain whether the acidity toward methyl red is due to free acid or to the hydrolysis and ionization of the small amounts of iron and aluminum salts present (ferrous and aluminum sulphates in aqueous solutions are both acid to methyl orange).
[d] At the time of analysis this water had deposited no sediment but on subsequent exposure to the air for several weeks all of the manganese deposited.
[e] Bromine and iodine if present are in minimal amounts.
[f] Twice the total reacting value of basic radicles.
[g] Twice the total reacting values of acid radicles.

Instead of distributing the error among all the acid or basic radicles it is in most analyses only necessary to distribute it among the group totals, as has been done for the first two analyses in the table. The results of the application of these methods to the two deep mine waters shown in the table are given in the following paragraphs:

Thermal water from Belmont mine, 1,500-foot level:

Alkali radicles balanced by strong acid radicles	58.4
Alkali radicles balanced by weak acid radicles	6.8
Alkali-earth radicles balanced by weak acid radicles	24.8
Metal radicles balanced by weak acid radicles	10.0
	100.0

The above statement shows that this water should be alkaline because of the presence of

alkali and alkali-earth carbonates which by hydrolysis and ionization give an excess of hydroxyl over hydrogen ions. Tests with phenolphthalein at the time of analysis gave an alkaline reaction. As noted on page 26, the water at the time of collecting did not appear to be alkaline toward phenolphthalein, but the test was made underground, and a faint pink coloration may have escaped detection. It is hardly probable that there was any appreciable absorption of alkali from the glass of the bottle in which the sample was shipped.

The water may be described as essentially a sodium and calcium sulphate and carbonate water which is somewhat alkaline and carries considerable manganese. In view of the absence of manganese in the Mizpah water it is not improbable that the Belmont water acquired its manganese content from manganiferous ores with which it came into contact.

Thermal water from Mizpah mine:

Alkali radicles balanced by strong acid radicles	61.2
Alkali earth radicles balanced by strong acid radicles	11.6
Alkali earth radicles balanced by weak acid radicles	25.6
Metal radicles balanced by weak acid radicles	1.6
	100.0

This is also essentially a sodium and calcium sulphate and carbonate water but has more than twice the concentration of the Belmont water and carries proportionately much more silica. No field tests with indicators are recorded by Spurr, but from the analysis this water would appear to possess only the very faint alkalinity attributable to alkali-earth bicarbonates. Unlike the Belmont water it carries no manganese. The presence of traces of nitrate in the Mizpah water is of interest in view of the known accumulation of nitrogen gas in the tops of certain stopes and raises at Tonopah.

Although both these waters are hot and the Mizpah water is clearly ascending from a considerable depth, there is nothing in their composition to indicate whether they come from an igneous source, or are surface waters that descended, became heated in some manner, and rose again toward the surface, or represent mixtures of waters from several sources.

No indications of the deposition of sulphides from these waters were found in the mines. As, according to the analyses, the waters contain no sulphur beyond that present in the sulphate radicle, there was probably no deposition of sulphides from them merely through a decrease in their pressure and temperature during their ascent. The deposition of sulphides and of certain native metals from sulphate solutions of this general character through reaction with earlier sulphides appears, however, to be possible. Such reactions may be metathetical, or they may involve reduction by the sulphides of certain metallic salts in the water. Iron and manganese, the only metallic components except aluminum sufficiently abundant to be determined in the water analyses would probably not be susceptible of such precipitation. The iron and manganese in these waters as they issued from the rock were already in a reduced condition incompatible with further reduction. As these metals stand at the end of the Schuermann series,[1] they are not likely to displace metathetically other metals from their combinations with sulphur. Certain other metals, however, notably silver, might if present be precipitated.

It may be concluded that these waters, if forming ore at all, are depositing sulphides or native metals only in small amounts by interaction with earlier sulphides.

It appears idle to speculate upon the possible relationship between these waters and the solutions that deposited the hypogene ores, either as regards origin or composition. They differ from those solutions at least in the absence of sulphides, for as the rocks that were replaced by the hypogene ores contained no minerals capable of reducing sulphates to sulphides, it is necessary to assume the presence of sulphides in the ore-depositing solutions.

SUPERGENE MINERALIZATION.

GENERAL CHARACTER.

Many of the hypogene ores have been extensively modified through the action of the air and of waters of surface origin descending through the lodes. The extent and degree of such action are dependent on the readiness with which the agents of alteration can gain access to the primary ores and are therefore intimately related to the nature and degree of frac-

[1] Schuermann, Ernst, Ueber die Verwandtschaft der Schwermetalle zum Schwefel: Liebig's Annalen, vol. 249, p. 326, 1888.

turing of the ores and wall rocks and the nature of the ground-water circulation. The complex history of the superficial alterations at Tonopah, involving two or more periods of oxidation subsequent to the primary mineralization, makes it unusually difficult to classify the alteration products in close accordance with the physical and chemical conditions under which they were formed. In the descriptions that follow they have been grouped according to their mode of occurrence as (1) residual products of oxidation and deposits in open spaces and (2) supergene replacement deposits.

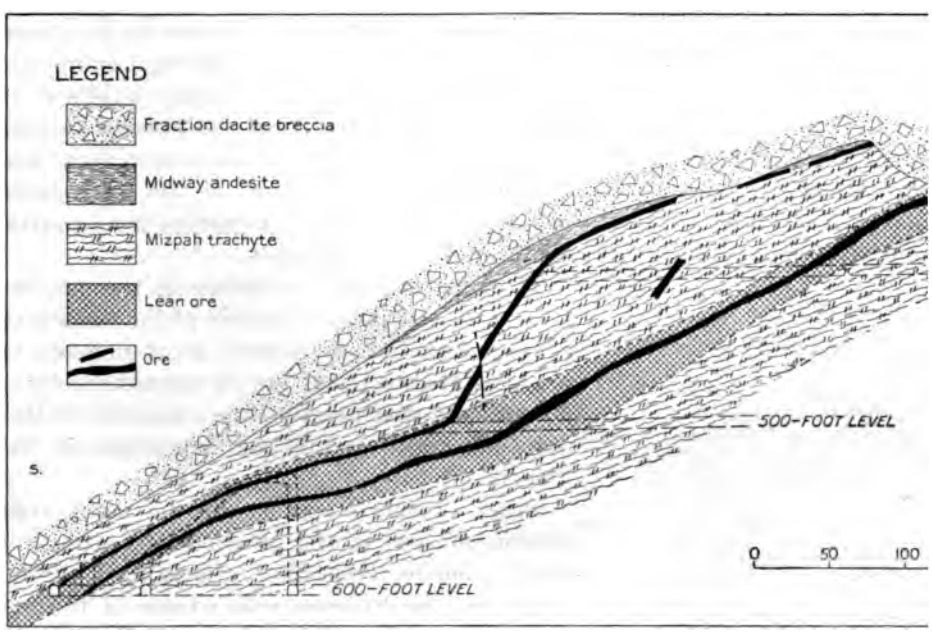


FIGURE 15.—Section through portion of West End mine showing structural relations of the Fraction dacite brecc to the Mizpah trachyte.

DEPTH OF OXIDATION.

General oxidation is characteristic only of the upper portions of the few veins that crop out. In the upper portions of the veins that do not crop out and in the deeper portions of the outcropping veins oxidation is local only. Such local oxidation was noted in some of the deepest workings near cross fractures that intersect the veins. It is well shown, for example, on the 770-foot level of the Tonopah Extension mine, the deepest level reached by the workings connected with the main shaft, where fractured ore and wall rock just above the Rainbow fault are much more oxidized than those at a distance from the fault. On the 600-foot level of this mine the Extension north vein is cut and offset by the Rainbow fault; for over 100 feet west of the fault plane pro shattered and is consider than the less shattered ore f oxidation near fractures wa Belmont vein on the 1,5(Tonopah Belmont mine. the Murray vein slight oxi the 1,170-foot level but nc or deepest level.

OXIDATION AT SEVEI

At a number of localitie is evidence of oxidation c the present surface but surfaces now deeply buriec ing evidence of this sort points near the 300 and 40 West End mine, where th End vein is capped for s Fraction dacite breccia. the West End mine th breccia is the surface rocl to have a general southwe 30° and truncates the Mi Mizpah trachyte, and in West End vein. The gen tions are shown in figure 1

The dacite breccia is, at a volcanic tuff, which, like rocks of the region, is belie of Tertiary age. Its tu suggested by its appearar

eye but is especially evident under the microscope, as shown in Plate X, *A* (p. 25). The specimen studied microscopically and figured in this illustration was obtained near station 1447 on the 300-foot level of the West End mine. It contains rock fragments irregularly angular in form and of various sizes and kinds; most of them are so much altered that their original character can not be determined; some show plagioclase phenocrysts in a finely granular ground mass. In addition, there are numerous fragments of quartz and feldspar phenocrysts, as shown in the illustration. The feldspar crystals are mostly andesine. A few of the feldspar crystals are perfect, but most of them are mere fragments, and many are very angular and irregular in form. Some are much fractured, not along cleavage

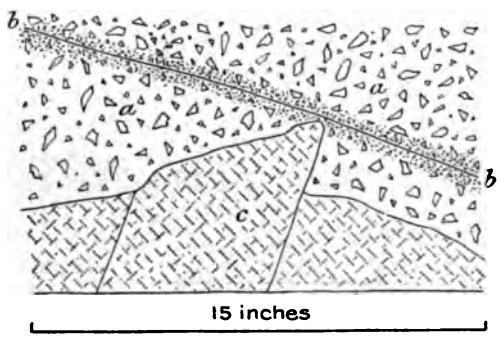


FIGURE 16.—Sketch of a portion of the contact between the Fraction dacite breccia and the West End vein in stope 309, West End mine. *a*, Unoxidized breccia; *b*, breccia oxidized near fracture; *c*, highly oxidized ore.

planes but very irregularly; the fractures do not extend into the inclosing matrix. One feldspar crystal may be much fractured and another very close to it may be unfractured, indicating that the fracturing took place before the crystals became embedded in their present matrix. Under high magnification (240 diameters) the matrix still appears fragmental and the fragments show diversity of size and shape. The smallest fragments are isotropic and are possibly volcanic glass. The alterations include partial calcitization of the plagioclase, some secondary enlargement of quartz fragments, and the development of chlorite in certain rock fragments.

That the breccia is younger than the ore of the West End vein is shown by the presence of a number of fragments of ore and pyritized wall rock in the breccia near its contacts with the vein.

Where the relations are not complicated by faulting the breccia appears to have been deposited directly upon the ore; in places it shows an obscure stratification parallel to the contact. Oxidation of the breccia near its contact with the vein is not general, but is usually confined to the vicinity of fractures, as shown in figure 16. Breccia in immediate contact with the vein may be wholly free from oxides of iron. The ore underlying the breccia, on the other hand, is as highly oxidized as much of the ore found at the present surface and carries iron oxides in mammillary and botryoidal forms. Some of the quartzose ore next to the contact is porous from partial solution of its constituents.

The high degree of oxidation in the ore, the unoxidized condition of much of the breccia in contact with the ore, and the local inclusion of oxidized fragments of ore in unoxidized breccia indicate that much of the oxidation of this ore took place before the deposition of the breccia.

Other evidence leading to the same conclusion consists in the presence of coatings of calcite, barite, crystalline quartz, and, rarely, pyrite on the hydrous iron oxides of the ore just below the breccia contact. (See Pl. X, *B*.) In ore from stope 484, not far above the 400-foot level of the West End mine, a coating of crystals of a carbonate of iron and calcium is deposited on hydrous iron oxides. Some barite is intergrown with the carbonate. On top of the carbonate occur well-formed crystals of clear quartz. Locally, quartz has replaced the exterior of scalenohedral crystals of calcite which rest on iron oxide. Ore from stope 400A shows thin coatings of pyrite on hydrous oxides of iron. These associations, except that of quartz, constitute mineral misalliances, for the minerals of the coatings are not normally formed during the oxidation of a sulphide ore. Their presence is, therefore, indicative of a change in the physical and chemical conditions surrounding this ore. The structural relations described on page 31 indicate that this change was brought about by the burial of an ancient, probably Tertiary gossan under a great thickness of volcanic

tuffs, inducing a return from surficial to deeper-seated conditions.

Spurr [1] calls attention to the probability of a still earlier period of denudation and oxidation between the deposition of the Mizpah trachyte and that of the Midway andesite. He says: "Most likely the earlier andesite [Mizpah trachyte] was deeply eroded and the veins were exposed before the later andesite [Midway andesite] was poured out." The contact between these two formations is in most exposures a fault contact, so that conclusive evidence of oxidation during this period could not be obtained.

From the evidence above set forth it may be concluded that although a part of the oxidation, even in those veins which do not crop out, is certainly recent, some is to be correlated with ancient, probably Tertiary land surfaces. As downward enrichment has been an accompaniment of the recent oxidation, it is logical to suppose that it was also an accompaniment of the ancient oxidation, and that there have, therefore, been several periods of downward enrichment.

GROUND WATER.

The common text-book diagram in which the water table is shown as a subdued counterpart of the land surface is applicable in a general way to regions, such as the Mississippi Valley, characterized by moderate humidity and flat-lying strata through which lateral circulation of ground water is easy, but it does not at all express the relations at Tonopah. In the Tonopah mines the active ground-water circulation is practically confined to zones of fracturing; copious flows are limited to a few such zones and usually to their more open parts. Other fractures have, for considerable periods at least, and to great depths, been sufficiently free from water to permit extensive oxidation through the agency of the atmosphere. These relations were emphasized by Spurr,[2] who says:

> No general body of ground water has been encountered, although the rocks are extremely fractured; yet along certain steeply inclined fracture zones water is found sometimes quite near the surface and occasionally in considerable quantity. This water is cool, is sufficiently nonmineral to be fair drinking water, and is undoubtedly the storage of precipitation.

[1] Spurr, J. E., Geology of the Tonopah mining district, Nev.: U. S. Geol. Survey Prof. Paper 42, p. 35, 1905.

[2] Idem, p. 107.

Spurr cites much evidence found in the sinking of shafts and driving of drifts illustrating the localization of the ground water in fractures. Observations from later mining experience, reported to the writers are wholly similar in their import and need not be enumerated here.

RESIDUAL PRODUCTS OF OXIDATION AND DEPOSITS IN OPEN SPACES BY SUPERGENE SOLUTIONS.

MINERALS NOTED.

The minerals listed below were noted either as residual untransported products of oxidation or as deposits in open spaces at a very late stage in the mineralization. As pointed out on page 42, certain of them, notably the sulphides, were formed as a rule at greater depths than others, but the fact that there have been several periods of oxidation makes it impracticable to define closely the conditions of formation of each mineral.

- Native elements:
  - Gold.
  - Silver.
- Sulphides:
  - Pyrite.
  - Chalcopyrite.
  - Argentite.
- Sulpho-salts:
  - Polybasite.
  - Pyrargyrite.
- Haloids:
  - Cerargyrite.
  - Embolite.
  - Iodobromite(?).
  - Iodyrite.
- Oxides:
  - Quartz.
  - Hyaline silica.
- Oxides—Continued.
  - Hydrous oxides of iron.
  - Oxides of manganese.
- Carbonates:
  - Calcite.
  - Mixed carbonates.
  - Malachite.
- Silicates:
  - Calamine.
  - Kaolin.
- Phosphate:
  - Dahllite.
- Sulphates:
  - Barite.
  - Gypsum.

GOLD.

Grains of bright-yellow gold large enough to be seen with the unaided eye are commonly confined to the much oxidized ores of the few veins that crop out. Such gold was abundant at a depth of about 100 feet in the Valley View vein, above and below a fault that displaces the vein. In specimens examined by the writers from the 500-foot level on this vein it forms minute flakes on oxidized surfaces, on which iodyrite and iodobromite were also deposited. Gold in association with iodobromite was also noted in abundance as golden-yellow grains 0.1 to 0.2 millimeter in diameter in the pan-

nings from soft oxidized ore from the South vein of the Desert Queen mine about 112 feet above the 600-foot level. Fractures in this ore are heavily coated with oxides of manganese.

The gold of the oxidized ores is commonly in larger grains than the hypogene electrum and, to judge from its yellow color, is of much greater purity. It is probably of supergene origin.

SILVER.

Silver occurs here and there in certain highly or moderately oxidized ores and in a very few places is fairly abundant. Argentite is in many places closely associated with it.

In the Tonopah Belmont mine native silver is present locally in the Belmont and Shaft veins. In the Belmont it was found from the 900-foot level, shortly below the "cap rock," down to the 1,400-foot level, though most abundant in the richest parts of the vein near the 1,100 and 1,166 foot levels; in the Shaft vein it was noted in ore from depths as far down as the 1,400-foot level. Silver was observed by the writers in ores from the MacDonald vein on the 330-foot level of the North Star mine and from vertical depths of 500 to 600 feet in the West End vein.

The silver may occur in wires, flakes, or tapering, fanglike forms commonly curling at the tip. The silver wires are found as a rule in matted aggregates in small vugs or open fractures, where they may be attached to quartz or barite crystals or to argentite. Ragged incrustations of silver on fractures and in small solution cavities were noted in ore from the 1,400-foot level on the Belmont vein, where they coat quartz or hydrous oxides of iron.

Small, bright flakes of silver of irregular outline on fractures in hypogene ore obtained between the 1,300 and 1,400 foot levels of the Belmont vein were not evenly distributed over the walls of the fractures but were deposited only where hypogene sulphides were abundant, suggesting that the sulphides exerted an influence in the silver precipitation. In some slightly oxidized ores of the Belmont vein the silver flakes are associated with a soft claylike material of blue-green color. Close study of this material shows that it is probably kaolin colored by an adsorbed soluble salt of copper. When pulverized and treated with cold aqua ammonia the blue material imparts the characteristic copper-blue to the solution. Acidification with hydrochloric acid yields no precipitate, showing that, contrary to the prevailing opinion among the miners, the blue material does not contain silver haloids. In this material are embedded flakes of silver and some grains of argentite, but crushing and panning may be necessary before they become visible. Local shearing since the silver was deposited has compacted the blue-green kaolin-like material into a talclike mass and drawn out the silver flakes into a very thin natural foil. Such shearing must be very recent.

Tapering, fanglike forms of silver were noted in ores from the Belmont, Shaft, and West End veins and commonly rise abruptly from a base of argentite or more rarely of polybasite; in some ores minute masses of argentite are attached to their sides or tips. Rarely the "teeth" are attached to a base of quartz or of barite. It is believed that the silver "teeth" have resulted from the reduction of silver compounds in place.

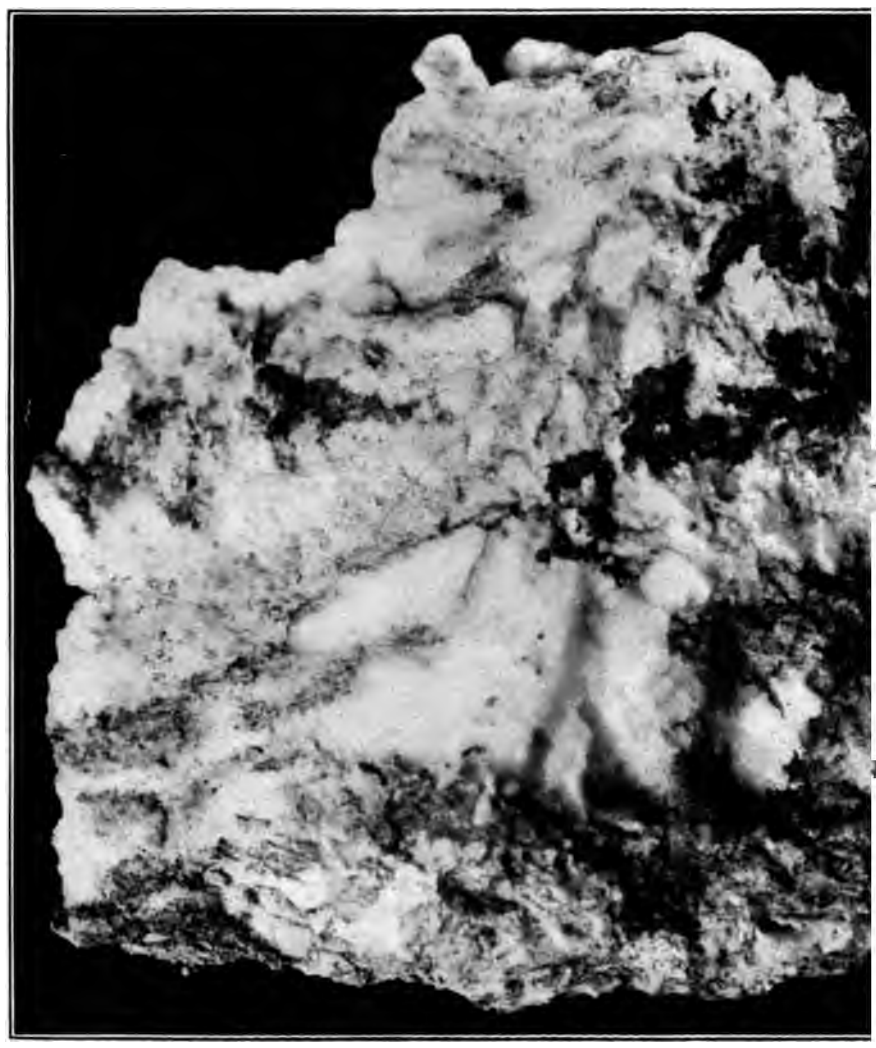
PYRITE.

Deposits of pyrite were noted in a few places coating fractures in hypogene ores to depths of about 600 feet. At several localities it is intergrown with barite, clear crystals of which in places completely inclose small pyrite pyritohedrons. Pyrite closely associated with barite was noted in fractures in the McNamara vein not far above the 300-foot level (344 raise) of the Tonopah Extension mine; in the Murray vein on the 600-foot level (end of 603 north crosscut) of the same mine; and in the West End vein on the 500-foot level (502 drift) of the West End mine. On the pyrite and barite locally ferruginous and manganiferous calcite, argentite, or both, have been deposited. In one place intergrown pyrite and quartz are deposited on earlier, more coarsely crystallized quartz coating a fracture in hypogene ore.

In all the late pyrite deposited in fractures in the Tonopah ores the predominant crystal faces are those of the pyritohedron, whereas in the pyrite of the undoubted hypogene ores and in the pyrite developed hydrothermally in the wall rocks cube faces predominate. That this contrast in crystal form signifies different conditions of deposition can hardly be questioned, but sufficient data are not at hand to warrant conclusions as to its precise significance.

A. BRANCHING DEPOSIT OF ARGENTITE, PROBABLY SUPERGENE, ON IN QUARTZOSE HYPOGENE ORE.

Small amounts of finely crystalline chalcopyrite are associated with the argentite. Spec Macdonald vein, North Star mine, in collection of A. E. Lowe, Tonopah.



B. LICHEN-SHAPED DEPOSITS OF ARGENTITE, PROBABLY SUPERGENE, ' BASITE, ON WALL OF FRACTURE IN HYPOGENE RHODOCHROSIT

Not far below 950-foot level, Murray vein, Tonopah Extension mine. Na

A. POLYBASITE, PROBABLY SUPERGENE, PARTLY FILLING FRACTURES IN WHITE, OPAQUE QUARTZ.

In a few places finely crystalline chalcopyrite and in one place a little native silver are deposited on the polybasite. Macdonald vein, Montana-Tonopah mine.

B. BRANCHING DEPOSITS OF PYRARGYRITE AND POLYBASITE, PROBABLY SUPERGENE, ON WALLS OF FRACTURE IN WHITE QUARTZ.

Montana-Tonopah mine, exact location uncertain. About natural size.

CHALCOPYRITE.

Small amounts of very finely crystalline chalcopyrite occur as late deposits along fractures in hypogene ore. In the Murray vein not far below the 1,000-foot level (203 stope) of the Tonopah Extension mine, chalcopyrite, polybasite, barite, and argentite have been deposited on crystalline quartz that coats fractures in hypogene ore. The sulphides are locally on or in the barite; elsewhere barite crystals lie on the sulphides. A part of the argentite in these fractures is an alteration from polybasite, for the exterior portions of flat hexagonal crystals of the typical polybasite form are now sectile argentite.

In the specimen from the MacDonald vein illustrated in Plate XII, *A*, finely crystalline chalcopyrite locally coats the polybasite in fractures only partly filled by polybasite. In the Fraction vein between the 600 and 700 foot levels of the Jim Butler mine argentite, locally intergrown with barite, coats fractures in hypogene ore; and on the argentite or intercrystallized with it are small crystals of chalcopyrite. Ore from the West End vein between the 700 and 800 foot levels shows intimate mixtures of argentite and chalcopyrite coating fractures in hypogene ore, also chalcopyrite, polybasite, and pyrargyrite in quartz-lined vugs.

ARGENTITE.

Argentite is particularly common as a late deposit on the walls of fractures cutting the hypogene ores. In one specimen from the Jim Butler mine it partly fills fractures in clean white quartz in much the fashion that polybasite does in the specimen shown in Plate XII, *A*. A branching deposit of argentite on a fracture in quartzose ore of the MacDonald vein is shown in Plate XI, *A*, and lichen-like deposits from the Murray vein are shown in Plate XI, *B*. These deposits lie directly on the hypogene ore; in other places a thin layer of crystalline quartz intervenes.

In many fractures argentite is accompanied by light-colored carbonates. In some places the argentite coats the carbonate, as in the Fraction vein between the 600 and 700 foot levels of the Jim Butler mine (stope 4), where siderite on a fracture is coated with a thin deposit of argentite about the area of a silver dollar. In other places argentite and carbonate are intercrystallized in a fashion suggesting contemporaneity. In fractures in the West End vein—for example, in a specimen taken between the 400 and 500 foot levels of the West End mine—argentite has been deposited over some crystals of ferruginous calcite; elsewhere on the same specimen the calcite coats the argentite, or the two are irregularly intercrystallized. In the Fraction vein between the 600 and 700 foot levels of the Jim Butler mine the the wall of a small fracture cutting hypogene ore is coated with slightly ferruginous calcite; over this in places is an intimate mixture of calcite, argentite, and some barite, the argentite in part inclosed by the calcite or barite; and on this mixture pure argentite is locally deposited. In the West End vein, between the 400 and 500 foot levels of the West End mine; the Fraction vein, not far above the 700-foot level of the Jim Butler mine; and the Murray vein in the 1,000-foot level of the Tonopah Extension mine argentite was noted entirely inclosed by clear barite crystals.

POLYBASITE.

Polybasite is common as a late deposit in fractures traversing hypogene ores; in some places it is intimately intergrown with pyrargyrite, and in many others it is closely associated with argentite. The first coating on such fractures is commonly crystalline quartz, the polybasite being deposited on this quartz.

In the Belmont vein on the 1,000-foot level of the Tonopah Belmont mine, near south crosscut 1044, fractures cutting hypogene ore are lined with finely crystalline quartz, on which thin patches of polybasite and argentite are deposited. A particularly fine specimen showing polybasite deposited along fractures in white quartz from the MacDonald vein is shown in Plate XII, *A*. In one part of this specimen a little native silver and in another part finely crystalline chalcopyrite were deposited on the polybasite.

Polybasite in fractures is locally associated with light-colored carbonates. In the Murray vein not far above the 1,100-foot level polybasite in some places lies on calcite and in others is coated by calcite, the two minerals being essentially contemporaneous.

PYRARGYRITE.

Late pyrargyrite that can be cleanly stripped from fractures and vugs in hypogene ores was noted in several places but was much less abundant than the pyrargyrite described on pages 14–15, which is believed to be hypogene. Such late pyrargyrite is also less abundant in general than late argentite and polybasite.

Pyrargyrite with intergrown polybasite and chalcopyrite was noted coating quartz crystals lining vugs in the West End vein between the 700 and 800 foot levels of the Jim Butler mine. The sulphides could be cleanly stripped from the quartz and were plainly deposited at a later period. Branching forms of late pyrargyrite intergrown with some polybasite on the wall of a fracture in white quartz in the Montana Tonopah mine are shown in Plate XII, *B*.

In ore rich in rhodochrosite from the West End vein between the 400 and 500 foot levels of the West End mine pyrargyrite and polybasite form thin coatings on the walls of fractures, from which they can be cleanly stripped. Specimens showing identical relations were obtained from the Tonopah Extension office, but their original location in the Extension workings is unknown.

SILVER HALOIDS.

Silver haloids were noted only in the veins that crop out. They were reported from several parts of the Tonopah Belmont mine. Specimens said to contain them were found to carry native silver and a soft blue-green material, probably kaolin, with adsorbed soluble copper salts, but no silver haloids were found. According to Burgess,[1] who had unusual opportunities for studying the occurrence of the silver haloids at Tonopah, the most abundant of them is cerargyrite, although most of the samples tested by him showed traces of bromine. All the gray silver haloids tested by the writers contained considerable bromine, but comparatively few specimens were available. There are evidently all gradations from cerargyrite into the chlorobromide embolite. Silver haloids, carrying chlorine, bromine, and iodine and others carrying bromine and iodine, were also noted. The pure bromide, bromyrite, was not noted, but nearly pure iodyrite is locally abundant. The colors of the silver haloids are in places deceptive, for much translucent pale-gray haloid appears to carry as much bromine as chlorine, and some pale-gray iodyrite was noted.

The mode of occurrence of these minerals presents a number of interesting features. In one specimen from the Tonopah Mining Co.'s upper workings (exact locality unknown) fractures in sulphide ore were coated with hydrous oxides of iron; on these was deposited a thin coating of malachite, which, in turn, was coated with calcite. Cerargyrite of dirty-gray color, carrying some bromine, is locally intercrystallized with the malachite and calcite. In one place the cerargyrite is wholly inclosed in calcite, but a short distance away it lies on unetched crystal faces of calcite.

A "sand" from porous oxidized ore from the Mizpah vein between the 400 and 500 foot levels carries yellowish iodyrite and a yellowish-green haloid without cleavage, that appears, upon testing,[2] to contain much bromine and less iodine and chlorine. The associated iodyrite is pale yellow, reacts only for iodine, and shows the hexagonal form and basal cleavage characteristic of that mineral.

In other specimens from the Tonopah Mining Co.'s upper workings (exact locality unknown) iodyrite that was deposited on the surface of iron oxide coating quartz is in part pale yellow and in part dirty gray in color. Both varieties are hexagonal, have perfect basal cleavage and yellow streak, and react only for iodine when tested in the closed tube. Some crystals are gray iodyrite at the base and yellow above. In parts of one specimen a first generation of iodyrite crystals has been coated with transparent colorless hyaline silica, and on top of this a later generation of smaller iodyrite crystals has been deposited. A centimeter or so away on the same surface, where hyaline silica is not present, there is only one set of iodyrite crystals, the later iodyrite appearing to have enlarged the earlier crystals without forming new ones. Locally iodyrite crystals are entirely inclosed by the hyaline silica, show-

[1] Burgess, J. A., The halogen salts of silver and associated minerals at Tonopah, Nev.: Econ. Geology, vol. 6, p. 17, 1911.

[2] The silver haloids were mixed with a little pulverized galena and heated before the blowpipe in the closed tube in accordance with the method recommended by Brush and Penfield (Manual of determinative mineralogy, p. 68, 1911). The lead chloride, bromide, and iodide formed are deposited at different heights in the tube and are easily distinguished from one another. Their relative amounts can be roughly estimated.

ing that the two minerals formed contemporaneously. Another specimen from the same mine shows hyaline silica deposited on iodyrite and iodobromite deposited on top of the silica; still another shows both iodyrite and iodobromite on silica that coats earlier iodyrite. The largest crystals of iodyrite seen were in a vug in oxidized ore, in a specimen from the Tonopah Mining Co.'s property, in the collection of J. A. Uhland. They measured three-sixteenths of an inch across the hexagon.

The relation of the silver haloids to the phosphate dahllite is considered on page 38.

QUARTZ.

Quartz is abundant as a coating on the walls of fractures traversing hypogene ores. It commonly forms continuous coatings from 1 to 3 millimeters thick composed of minute colorless, transparent hexagonal crystals. It is usually the first coating on such fractures, and on it barite, carbonates, kaolin, polybasite, argentite, pyrite, chalcopyrite, and a few other minerals are locally deposited. These quartz coatings are possibly late hypogene, as noted on page 18.

HYALINE SILICA.

A number of characteristic occurrences of hyaline silica are described in the sections on silver haloids and dahllite. The mineral was also noted coating psilomelane in the Valley View vein on the 400-foot level. It is not confined to the veins but occurs abundantly at the surface as thin coatings along joints in the Midway andesite.

OXIDES OF IRON AND MANGANESE.

The presence of rhodochrosite in the hypogene ores has led to an abundance of hydrous oxides of manganese in the products of their oxidation. These are rarely pure, being mixed usually with hydrous oxides of iron. In the Belmont vein between the 1,300 and 1,400 foot levels there are masses a foot or so across composed almost wholly of these oxides. Thin exterior coatings of dark reddish-brown pulverulent oxides coat a porous framework of hard gray metallic oxides that give an ocher-yellow streak. On the 1,300-foot level on the same vein a lens of pulverulent manganese oxide 10 inches wide and 2 feet long was noted at one place. The material is dark dull gray and finely crystalline, gives a dark-brown streak, and is probably manganite.

CALCITE.

Calcium carbonate nearly free from iron, manganese, and magnesium is much less common than the mixed carbonates described below and was noted in only a few places. Colorless calcite carrying a trace of manganese was noted in the Belmont vein on the 800-foot level of the Tonopah Belmont mine as a crystalline coating on fractures traversing coarse hypogene sulphide ore. In places this calcite is intergrown with crystals of polybasite, the two being apparently contemporaneous. Calcite was also noted coating malachite in ore from the Tonopah Mining Co.'s property.

MIXED CARBONATES.

Qualitative tests on many of the carbonate coatings on fractures in hypogene ore show the presence of two or more of the elements iron, manganese, calcium, and magnesium. Many carbonates that are pure white in color are notably ferruginous and turn brown on heating. Manganese in many places accompanies the iron, but its proportion appears less than in most of the hypogene carbonates, for a pink color was nowhere noted.

MALACHITE.

Carbonates of copper are not at all common in the ores now visible at Tonopah. In a specimen from the property of the Tonopah Mining Co. (exact location unknown) a fracture in the hypogene ore is coated with hydrous iron oxides; on these locally malachite and gray cerargyrite carrying some bromine have been deposited. Both these minerals are in places coated with transparent colorless calcite.

CALAMINE.

Characteristic "sheafs" of the hydrous zinc silicate calamine were noted in the West End vein between the 500 and 600 foot levels (stope 600 C) of the West End mine. A fracture in the sulphide ore was first coated with a thin layer of crystalline quartz; on this argentite and siderite were deposited; oxidation followed, converting part of the siderite to

hydrous iron oxides and rendering the argentite dull and locally pulverulent; and finally calamine was deposited on the iron oxide.

KAOLINITE.

A white pulverulent infusible material that reacts strongly for alumina but not for potassium [1] is common in the vugs and pores of many of the ores. Microscopic examination shows that this material is an aggregate of minute, roughly spindle-shaped crystals of quartz and another mineral of nearly the same index of refraction but of very low double refraction. This second mineral, which is probably kaolinite, is in too minute grains to permit the determination of its optical constants.

Kaolinite has been one of the latest minerals to form in the Tonopah ores. Locally it occupies spaces formed by the solution of hypogene quartz or carbonates; elsewhere it has been deposited on argentite, polybasite, and carbonates that appear to be of supergene origin. In a specimen from a vertical depth of 1,395 feet on the Shaft vein (east stope 3) in the Tonopah Belmont mine kaolinite has been deposited subsequent to the formation of wires of native silver, which it locally coats. Its presence was noted in ores from the deepest workings; it is common in unoxidized ores; and where it occurs in oxidized ores its development has preceded oxidation except where, as shown by other evidences, there has been a return from oxidizing to deeper-seated conditions.

Kaolinite is not confined to the ores but is common in the neighboring wall rocks. In the north crosscut on the 850-foot level of the North Star mine, for example, it forms the matrix of rock fragments in a brecciated zone in the Mizpah trachyte.

Much of the kaolinite occurring in the ores is not a purely residual product but is either a precipitate from solution or has been introduced in suspension. This is shown by its mode of occurrence in certain quartz-lined vugs, where it is heaped up like snow on a fence top on the upper sides of the quartz crystals and is relatively scarce on their under sides.

[1] The material was tested for alumina by moistening with cobalt nitrate and heating before blowpipe; for potassium by the flame coloration test.

DAHLLITE.

The presence of dahllite, the calcium carbono-phosphate ($3\ Ca_3(PO_4)_2.CaCO_3$), at Tonopah was first recognized by Rogers [2] in ore from the Mizpah mine. This ore also contained iodyrite, hyaline silica, quartz, and manganese dioxide. The dahllite formed small white tabular crystals of hexagonal outline resembling apatite in form but effervescing with warm nitric acid.

The same mineral was observed by the writers in ore from the Valley View vein just below the 400-foot level. It forms short hexagonal prisms 0.5 millimeter or less in diameter that effervesce slightly with cold nitric acid and react for phosphorus with ammonium molybdate. The dahllite crystals lie upon quartz crystals lining vugs and also upon hydrous oxides of iron, and on the dahllite in turn silver haloids are deposited. All these minerals are covered locally by clear, colorless hyaline silica. Of the silver haloids olive-green iodobromite was first deposited, and on this and also on the dahllite is iodyrite.

In another ore specimen from the Tonopah Mining Co.'s workings (exact locality unknown) dahllite occurs both in and on hyaline silica coating oxidized surfaces.

It is apparent that the dahllite was deposited under the same conditions as the silver haloids and hyaline silica.

BARITE.

Barium sulphate is fairly abundant in well-formed crystals on fractures traversing hypogene ore; commonly the first coating is quartz and the barite crystals lie on that. In many places the barite was clearly deposited contemporaneously with one or more of the minerals pyrite, argentite, and polybasite, grains of these sulphides being wholly inclosed by the barite. In other places barite is the only coating on the fractures or on the quartz lining the fractures.

GYPSUM.

Selenite crystals are not uncommon in the oxidized ores, especially in the veins that crop out. Abundant selenite was observed in the

[2] Rogers, A. F., Dahllite (podolite) from Tonopah, Nev.: Am. Jour. Sci., 4th ser., vol. 33, pp. 475–482, 1912.

South vein of the Desert Queen mine on the 700-foot level, where it occupies fractures in oxidized ore. Pyrolusite is the most abundant oxidation product there, and the selenite lies on the pyrolusite, being clearly of later formation.

EPSOMITE.

Crystals of hydrous magnesium sulphate were noted in the West End mine on the 400-foot level (near raise 415 B), where they had been deposited recently near cracks on the walls of the drift by the evaporation of water used in wetting down the stopes. The epsomite may have been an original constituent in the water supply or may have been acquired by the water through reaction with the waste in the stopes.

SUPERGENE REPLACEMENT DEPOSITS.

REPLACEMENT OF CHALCOPYRITE BY BORNITE (?), COVELLITE, AND ARGENTITE.

In the processes of mineralization thus far described chalcopyrite has replaced other minerals but has not itself been replaced. In other words, chalcopyrite has behaved as a stable mineral under the conditions of supposed hypogene mineralization.

In an ore specimen from the Shaft vein on the 1,000-foot level of the Tonopah Belmont

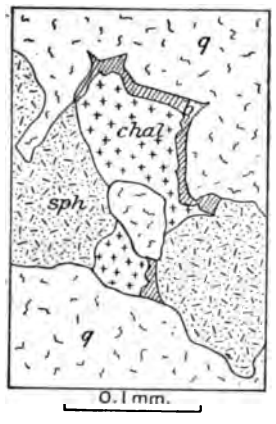


FIGURE 17.—Replacement rim of probable bornite (*b*) bordering chalcopyrite (*chal*). *q*, Quartz; *sph*, sphalerite. Camera lucida drawing from polished surface of ore from Shaft vein, 1,000-foot level of Tonopah Belmont mine.

mine, examined under the microscope, chalcopyrite has been replaced by what is probably bornite and this in turn by covellite, argentite, or an intergrowth of these two minerals, as shown in figures 17 and 18.

The supposed bornite rims around chalcop
rite showed the purplish color usual in fres
polished bornite. The quantities being mic
scopic, it was impossible to isolate any of t
minerals for analysis. It is known that ch
copyrite immersed in silver sulphate soluti
soon becomes coated with a tarnish resembli
bornite, probably a sulphide of silver and ir
as Palmer [1] has shown. This mineral is of cou

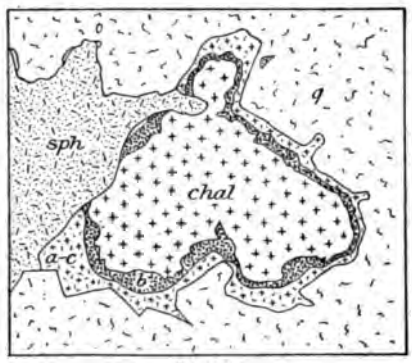


FIGURE 18.—Peripheral replacement of chalcopyrite (*chal*) by prob
bornite (*b*) which is in turn partly replaced by a fine intergrowt
argentite and covellite (*a–c*). *q*, Quartz; *sph*, sphalerite. Cam
lucida drawing from polished surface of ore from Shaft vein, 1,000
level of Tonopah Belmont mine.

stable in contact with silver sulphate soluti
To determine whether the bornite-like ri
were this mineral, they were treated with silv
sulphate solution. They tarnished in the sa
manner as known bornite from Virgilina, V
and are believed to be bornite. The covell
shows the characteristic blue color. There
gradations from apparently pure covell
through fine intergrowths of covellite a
supposed argentite into areas that are unqu
tionably pure sectile argentite. When the f
intergrowths were treated with silver nitr
solution the covellite became gray and ind
tinguishable in tint from the supposed arg
tite with which it was intergrown. As it
well known that covellite changes to argent
on treatment with silver nitrate, the iden
fication of both minerals appears reasonab
certain.

The close association of covellite and arg
tite is of interest in view of the known capac
of covellite to form silver sulphide (Ag
when treated with silver nitrate or silver s

[1] Palmer, Chase, Bornite as silver precipitant: Washington Acad.
Jour., vol. 5, pp. 351–354, 1915.

phate solution.[1] In this specimen the argentite appears not to be a replacement of the covellite but to be contemporaneous with it. Covellite alone peripherally replacing chalcopyrite was noted in ore from the West End vein a short distance above the 600-foot level (stope 600 C). Areas of pyrite adjacent to the chalcopyrite have not been replaced by covellite.

REPLACEMENT OF SPHALERITE AND GALENA BY COVELLITE OR ARGENTITE OR A MIXTURE OF THESE MINERALS.

In other parts of the specimen from the Shaft vein mentioned in the preceding section, covellite and mixtures of covellite and argentite were noted as formed by the replacement, mainly peripheral, of galena and sphalerite.

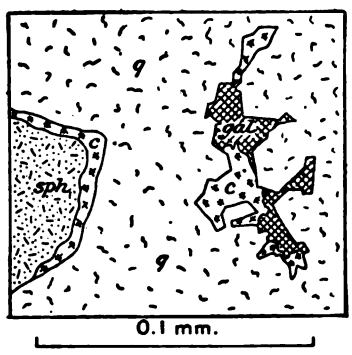


FIGURE 19.—Replacement of galena (*gal*) and sphalerite (*sph*) by covellite (*c*). *q*, Quartz. Camera lucida drawing of polished surface of ore from Shaft vein, 1,000-foot level of Tonopah Belmont mine.

These replacement deposits are shown in figures 19 and 20. In the supposed hypogene replacement deposits described on pages 19–25 sphalerite was rarely attacked, being in general stable under hypogene conditions.

In the specimen shown in figure 20 the width of the replacement rim does not change in passing from parts that are wholly argentite to parts that are wholly covellite. This feature was also noted in replacement borders of argentite and electrum developed around galena, as shown in Plate IX, *B*. In other parts of the same specimen galena is replaced by argentite, but there is a transition band of the unidentified galena-like mineral between the argentite and the galena.

[1] Anthon, E. F., Ueber die Anwendung der auf nassem Wege dargestellten Schwefelmetalle bei der chemischen Analyse: Jour. prakt. Chemie, vol. 10, p. 353, 1837. Posnjak, Eugene, Determination of cupric and cuprous sulphides in mixtures of one another: Am. Chem. Soc. Jour., vol. 36, pp. 2475–2479, 1914.

NATIVE SILVER.

In the specimen from the Shaft vein in which the replacement deposits described above were noted small areas of native silver

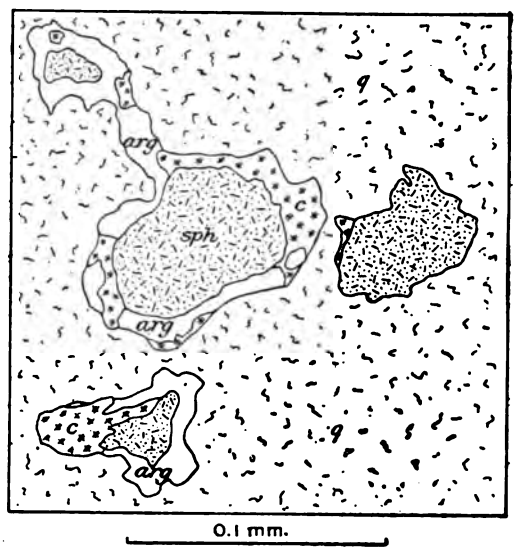


FIGURE 20.—Peripheral replacement of sphalerite (*sph*) by an association of covellite (*c*) and argentite (*arg*). *q*, Quartz. Camera lucida drawing of polished surface of ore from Shaft vein, 1,000-foot level of Tonopah Belmont mine.

are abundant. The silver-bearing parts of the specimen are commonly more or less porous and are apparently the most altered parts of the ore. The silver is usually associated with argenite and may, at least in part, replace it, as suggested by the relations shown in Plate XIII, *A*. In other parts of the same specimen, as shown in figure 21, silver and argentite

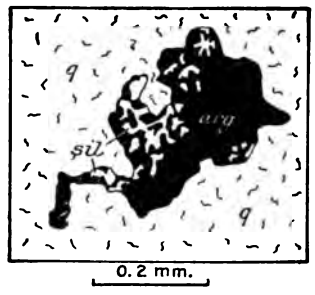


FIGURE 21.—Association of argentite (*arg*) and native silver (*sil*). Both minerals are probably a replacement of some hypogene sulphide. *q*, Quartz. Camera lucida drawing of polished surface of ore from Shaft vein, 1,000-foot level of Tonopah Belmont mine.

are so irregularly intergrown as to suggest contemporaneity.

As electrum is so common in the ores as a hypogene mineral, it would appear theoretically possible that native silver should occur

A. ASSOCIATION OF SILVER (*sil*) AND ARGENTITE (*arg*) SUGGESTING SULPHIDE BY THE NATIVE METAL.

Photomicrograph of polished surface of ore from 1,000-foot level, Shaft vein, Tonopah boundaries have been outlined to render them more distinct. The knob of p surrounded by soft porous material which shows black in the photograph.

B. OXIDATION BANDING IN MIZPAH TRACHY

From walls of Valley View vein. Natural size.

A. OXIDATION BANDING IN MIZPAH TRACHYTE ADJACENT TO VALLEY VIEW VEIN.

About two-thirds natural size. Small crystals of pyrite are abundant in the unoxidized portion (*A*) but are absent from the banded portion of the vein.

B. OXIDATION BANDING IN FINE, EVEN-GRAINED FELSITE.

Near North Star shaft. Natural size.

also as a hypogene ore mineral. Close study of the ores, however, has failed to discover native silver in any situation where a supergene origin is not more probable than a hypogene origin. Furthermore, as gold was fairly abundant in the hypogene solutions, electrum would seem to be the more likely mineral to form.

RELATION BETWEEN SUPERGENE ENRICHMENT AND FRACTURING.

Deposition in open spaces and metasomatic replacement have both taken part in the supergene mineralization, but the former method of deposition has greatly predominated. Characteristic deposits of argentite, pyrargyrite, polybasite, chalcopyrite, pyrite, native silver, barite, and carbonates on fractures cutting the hypogene ores are described above. The effect of such deposits on the average tenor of the ore in certain parts of a vein is in many places masked by the somewhat sporadic distribution of the hypogene replacement deposits; nevertheless a distinct relationship between late fracturing and ore tenor is recognizable in a number of places.

On the 1,050-foot level of the North Star mine (see fig. 22) the MacDonald vein west of the point where it was cut by the eastward-dipping North Star fault was not of exceptional grade; just east of or above this fault occurred the richest silver ore the mine has produced, carrying an abundance of pyrargyrite, argentite, etc. The value of the ore decreased from the fault eastward and in the 100 feet west of winze 1,050 fell to $3 or $4 a ton. Low assays continued up to a northerly fault dipping 65° E. Just east of or above this fault high-grade ore averaging 0.3 ounce of gold and 30 ounces of silver to the ton was found for about 30 feet. Examination of this ore showed argentite along fractures in thin layers that could be readily stripped off and that are probably of supergene origin. There is half an inch or so of gouge along this fault, but the vein is not greatly displaced by it.

In the Extension No. 1 workings ore tenor in the Extension North vein appears to have been influenced by the degree of fracturing near the Rainbow fault, which trends north-northeast and is not itself mineralized. The zone of maximum movement along this fault is marked by 2 feet of gouge dipping 50°–60° E. The North vein west of this gouge was little shattered, and its ore was not notably rich, but for 120 feet east of the gouge the vein was intensely shattered without serious displacement, was much oxidized, and was of high grade.

According to Mr. J. H. Dynant, of the Tonopah Extension Co., the ore of the McNamara vein on the 400-foot level was notably richer close to the Rainbow fault than away from it on either side. The fractured zone here is at least 20 feet wide, and the ore is highly brecciated and oxidized.

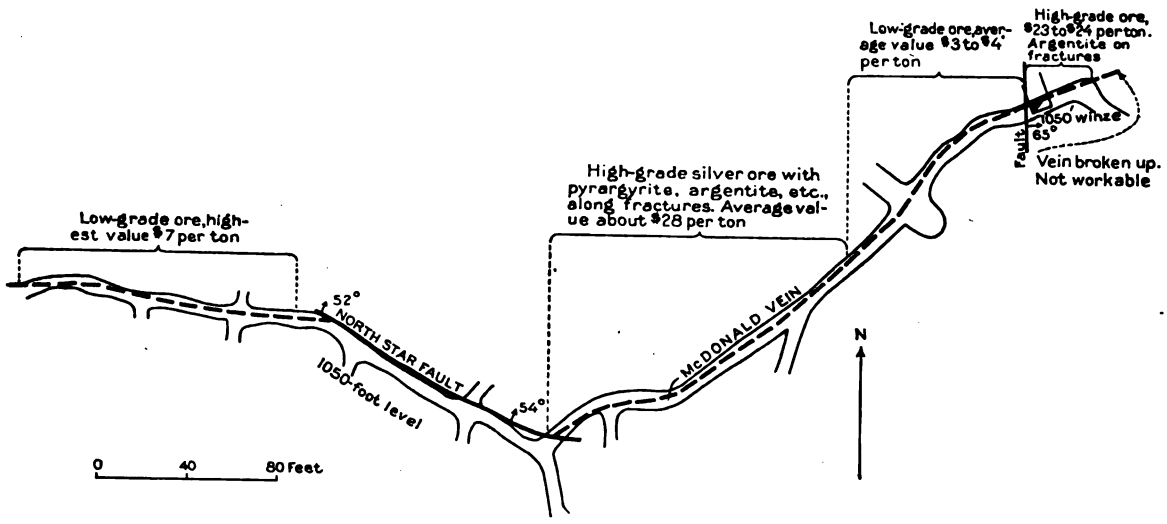


FIGURE 22.—Plan of a portion of the North Star mine workings, showing the relations between supergene enrichment and fault fractures.

In the Tonopah Extension and West End, mines the most persistent and conspicuous fractures traversing the veins strike N. 10°–30° E. and are nearly vertical. Along most of these fractures the displacement has been slight, but some of the larger faults of similar trend and considerable displacement, such as the Rainbow fault, may belong to this series. Late deposits of argentite, polybasite, and carbonates are common along these fractures, which appear to have been influential in guiding the enriching solutions.

Just above the 500-foot level of the West End mine in stope 505 the West End vein, which strikes N. 80° W. and dips 35° N., is cut by a vertical fault striking N. 10° W. For 50 feet from the main fault the ore is traversed by a number of parallel subsidiary fractures. The ore of this 50-foot interval is said by Mr. J. W. Chandler to have been notably richer than that on either side. Examination showed that it carried argentite, chalcopyrite, barite, and ferruginous calcite on fractures.

In the Tonopah Belmont mine no such regular and extensive system of fractures traversing the ore was noted as in the western part of the camp, and it was reported that the few well-defined fractures that occur appear not to have influenced greatly the tenor of the ore. A probable exception to this statement is the Belmont fault, for some of the richest ore of the mine has been found in the Belmont vein for 50 feet east of (above) this fault on the 1,100 and 1,166 foot levels, where the ore was much fractured and oxidized. Irregular minor fractures are numerous in the ores of this mine, and it is probable that most of the ore was fairly permeable to descending solutions.

SUMMARY OF EVIDENCE OF SUPERGENE ORIGIN OF CERTAIN ORE MINERALS.

The supergene origin of the deep-yellow gold, silver haloids, hyaline silica, hydrous oxides of iron, oxides of manganese, malachite, calamine, dahllite, gypsum, and epsomite in the Tonopah ores is not open to queston.

The silver haloids are evidence of solution and redeposition of silver in the oxidized zone, and it is certainly to be expected that some of the silver taken into solution would be redeposited at greater depths as the sulphide or sulphosalts of silver. The notable enrichment of the MacDonald vein above certain inclined faults (see p. 41) by deposits of pyrargyrite and argentite on fractures is concrete evidence that such deposition has taken place.

The thin coatings of crystalline quartz common on fractures may be of diverse origin and age. Though clearly formed after the main hypogene mineralization and after the ores had been fractured, some of this quartz was probably deposited by ascending solutions, as is shown by the presence of wolframite, an undoubted hypogene mineral, intergrown with such quartz in parts of the Belmont vein. Other quartz coatings are probably supergene, as for example those on oxidized ore below the Fraction dacite breccia. Not all the late fractures are coated with quartz, but where quartz is present it usually forms the first coating and the late silver minerals lie on the quartz, not intercrystallized with it.

Structural evidence of the supergene origin of some of the argentite, polybasite, and pyrargyrite in the ores has been presented, but the supergene origin of all occurrences of these minerals in late fractures and of the pyrite, chalcopyrite, barite, and carbonates in places associated with them can not be said to have been proved. Some of them may have been deposited by ascending solutions at a period distinctly later than the main hypogene mineralization, or by interaction between ascending and descending solutions. If they are hypogene they are probably later than the period of oxidation which preceded the deposition of the Fraction dacite breccia, for barite, calcite, and rarely pyrite coat highly oxidized ore just below this breccia. (See p. 32.) The writers believe that the probabilities favor the supergene origin of all the minerals except wolframite and a part of the quartz, which coat sharp-walled fractures cutting the typical hypogene ores.

Native silver appears to be absent from the deeper ores at Tonopah, even from those that carry argentite and sulphosalts of silver in abundance. It was noted only in ores that were somewhat oxidized, were more or less porous through solution of certain constituents, or showed other evidences of alteration, such as the presence of kaolin containing adsorbed soluble salts of copper. In places, its relations suggest that it has been formed by the alteration of argentite or polybasite. All the native

silver at Tonopah is, therefore, believed to be supergene.

The replacement of chalcopyrite by bornite, of bornite by covellite and argentite, of sphalerite by covellite and argentite, and possibly of argentite by native silver, shown by a specimen from the Shaft vein, contrasts strongly with the replacement characteristic of most of the Tonopah ores. Under the conditions of the more usual and supposedly hypogene replacement chalcopyrite is stable (being itself a replacing mineral), argentite is never accompanied by native silver but on the contrary is in places accompanied by electrum, and sphalerite is only rarely replaced and then not by covellite and argentite but by chalcopyrite and polybasite. Obviously, these types of replacement occurred under physical and chemical conditions quite different from those under which most of the ores were formed. The loss of iron and the substitution of silver for copper involved in the replacement of chalcopyrite by bornite and of bornite by argentite, as well as the formation of native silver, are changes in harmony with well-known chemical tendencies in supergene enrichment, and to this process the writers attribute them.

NATURE OF SOLUTIONS PRODUCING SUPERGENE MINERALIZATION.

Where active oxidation of pyrite and chalcopyrite was in progress, acidity must, at least locally and transiently, have been imparted to the waters in contact with the ore. The abundance of primary carbonates (of one or more of the elements calcium, magnesium, iron, and manganese) in most of the Tonopah ores, however, favors the neutralization of acidity early in the descent of the solution. This inferential conclusion appears to tally with the observed facts, for, as shown in the detailed descriptions that precede, the argentite and polybasite in late fractures are in many places intergrown with or even wholly inclosed in calcite or related carbonates. Such mineral associations were evidently deposited by neutral or possibly alkaline and not by acid solutions. If such deposits in fractures have been correctly interpreted as supergene, it follows that the supergene solutions were not acid at the places at which these minerals were deposited, whatever may have been their reaction earlier in their descent. Even the silver haloids were, locally at least, deposited by neutral solutions, a
their intercrystallization with m
calcite. Barite is associated wit
supergene argentite and polybasite
same manner as the carbonates.
ogic evidence indicates therefore
solutions which produced super
ment became neutral early in the
journey; (2) that they carried ca
sulphates in abundance, with lesse
halogens and phosphates; and (3
transported silver, copper, iron,
arsenic, antimony, and possibly

In the hope of obtaining further
cerning the character of the soluti
duced the supergene enrichment,
descending mine water was coll
West End mine and was analyz
Palmer. (See table on p. 29).
flowed down through the broken o
filling of a large caved stope betw
and 500 foot levels and issued in a
at raise 524 on the 500-foot level.
it is in contact with ore and with th
conditions simulate those original
short distance below the natural o
veins. The water as tested in the
cidedly acid to methyl orange an
holes where it dripped on corrug
the foot of raise 524.

The analysis shows that this is
sodium and calcium sulphate wa
also manganese and chlorine radic
ance. Its concentration is nearly
of the Mizpah deep water and near
that of the Belmont deep water.
relations between its components,
accordance with the Palmer met
follows:

Alkali radicles balanced by strong acid rad	
Alkali earth radicles balanced by strong a cles	
Metallic radicles balanced by strong acid r	
Free strong acid (?)	

The slight excess of strong aci
the analysis is within the permissi
experimental error, and it is ther
tain whether the observed acidity
toward methyl orange is due to
of free acid (SO_4 in balance with
hydrolysis and ionization of the sm
of salts of strong acids and weak b

ferrous and aluminous sulphate in aqueous solution both giving acid reactions. The entire absence of carbonate and bicarbonate radicles, in spite of the fact that the water has percolated through carbonate-bearing ore, is a natural consequence of the acidity of the water, as a result of which carbonates would be converted into sulphates with liberation of carbon dioxide.

It appears that this water may present some analogy to the waters that accomplished the supergene enrichment in the early part of their descent, before neutralization and before they had acquired their full load of dissolved materials. It is apparently not an analogue of the supergene solutions at the stage when they deposited most of the supergene silver minerals, for at that stage they appear to have been neutral and were depositing also carbonates.

PROBABLE PERSISTENCE OF ORES IN DEPTH.

The deepest developments in the Tonopah mines have shown that in certain veins the degree of mineralization gradually decreases with increasing depth. The deep ores of such veins carry more quartz and less sulphides than the ores higher up; microscopic study shows, however, that the sulphides are the same species as in the ores above and that replacement deposits of the type described as probably hypogene are present, though naturally not in such abundance as in the ores richer in sulphides. The Belmont vein on the 1,500-foot level of the Tonopah Belmont mine, the combined vein on the 770-foot level of the Extension No. 1 workings, and the Favorite vein on the 1,200-foot level of the Tonopah Belmont mine afford good examples of such diminution in value with depth.

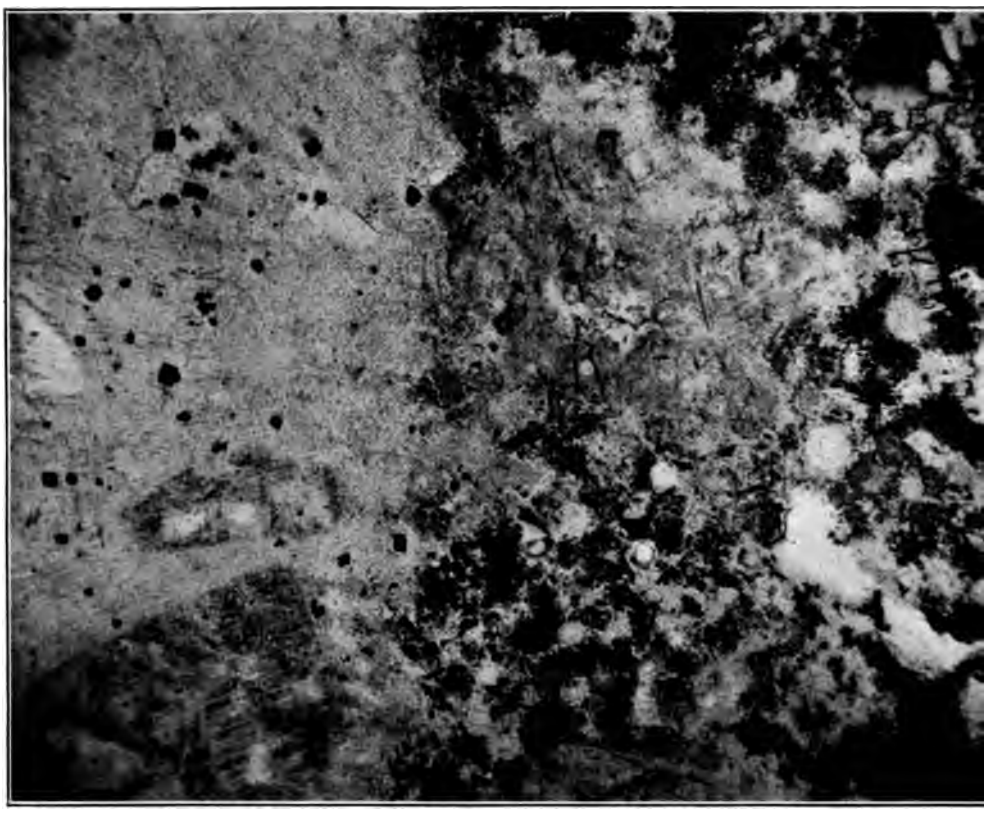
The Belmont vein on the 1,500-foot level shows sulphides only in a few places; much of it is brecciated wall rock traversed by veinlets of white or dark-gray quartz, and no ore in commercial quantity has yet been found. Ore from a point 40 feet east of raise No. 2, when examined microscopically, was seen to carry scattered grains and small aggregates of galena, sphalerite, chalcopyrite, pyrite, and polybasite in a quartz gangue. The polybasite, at least in part, replaces galena, and there are narrow transition rims of probable lead-silver sulphide between. A sample of this ore assayed by the Bureau of Mines showed 0.08 ounce of gold and 3.90 ounces of silver to the ton. The hand specimen shows very slight oxidation along fractures, and kaolin occurs as a late deposit on the quartz crystals in some vugs.

Ore from the 770-foot level of the Extension No. 1 workings is highly quartzose and carries scattered minute grains of pyrite and, rarely, small dark-colored aggregates of other sulphides. A polished surface of a piece comparatively rich in dark sulphides shows galena, sphalerite, pyrite, chalcopyrite, and polybasite. The polybasite is peripherally replaced by an aggregate of argentite and chalcopyrite. The hand specimens show hydrous iron oxides along some fractures and manganese oxides along others.

In contrast to the veins just mentioned, other veins show strong mineralization on the deepest levels to which they have been developed. Ore from the Murray vein, for example, on the 1,260-foot level, is rich in sulphides and is equal in grade to much of the ore higher up. This ore is unoxidized. Microscopic study of a polished specimen shows the presence of galena, sphalerite, pyrite, and chalcopyrite, in addition to quartz and a pink manganiferous carbonate. In places the galena has been peripherally replaced by argentite and electrum, as shown in Plate IX, *B*. Some kaolin has been deposited in small vugs.

The decrease in tenor with increasing depth in the veins of the Tonopah Belmont mine is concomitant with the passage of the veins from the Mizpah trachyte into the West End rhyolite and is doubtless dependent, at least in part, upon the differing susceptibilities of the two rocks to fracturing and replacement. The mineralization, though varying in degree, was continuous from one formation to the other.

Although obviously all veins must terminate in depth as well as laterally, the evidence from microscopic studies that many of the silver minerals at Tonopah are hypogene (primary) and that they occur in ore from the deepest workings offers substantial encouragement to deep mining. In some veins change in wall rock was probably a more important factor than mere increase in depth in causing the decreased ore tenor.

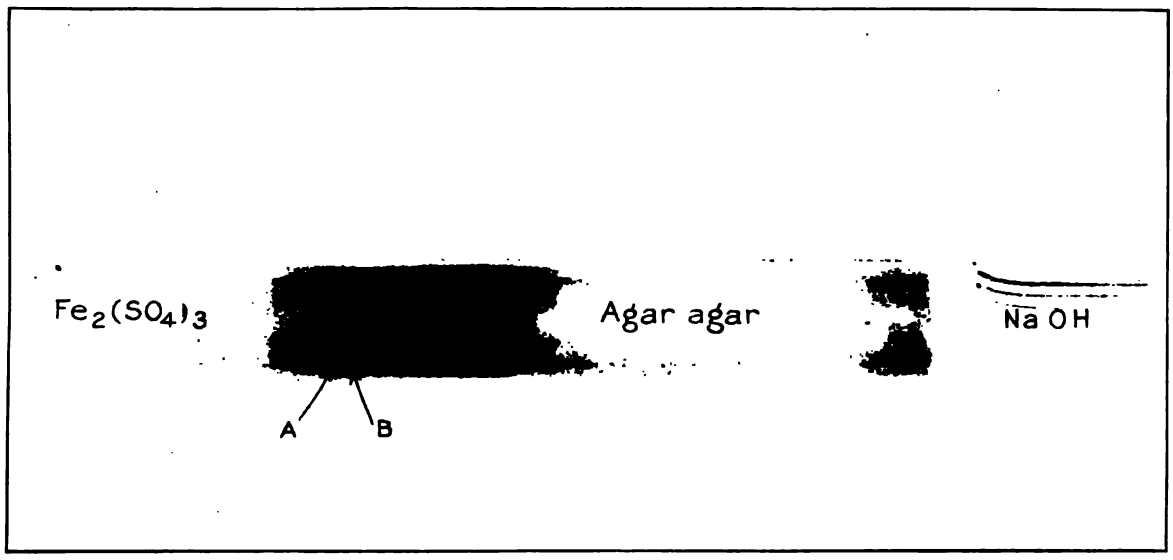


A.

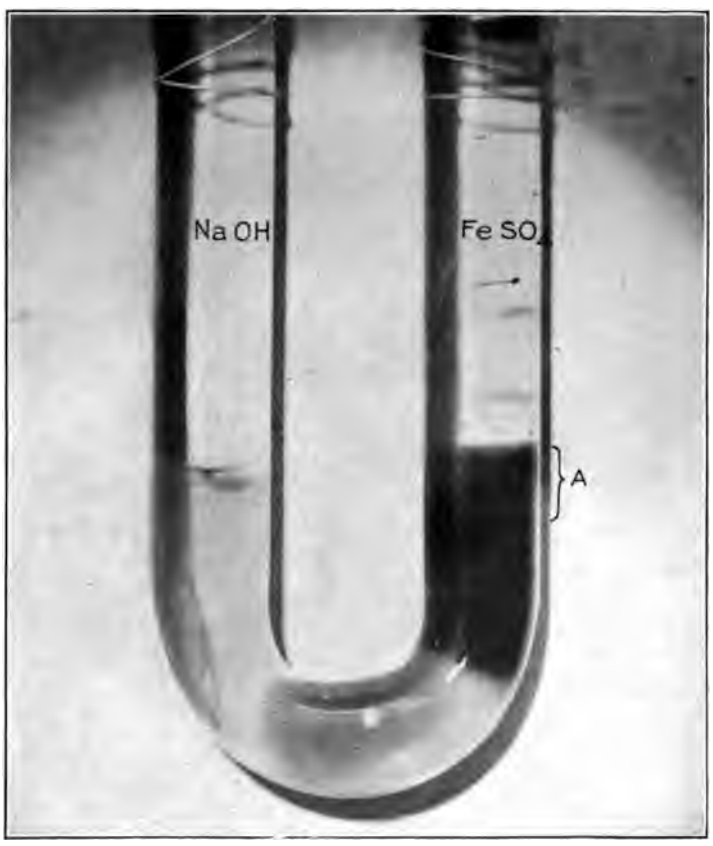
B.

PHOTOMICROGRAPHS OF CONTACT BETWEEN OXIDIZED AND UNOXIDIZED PORTIOI SPECIMEN SHOWN IN PLATE XIV, *A*.

A was taken in ordinary light and *B* in polarized light. In the unoxidized half, as shown at the left in *A* pyrite crystals abound; in the oxidized half the iron occurs as finely divided oxide, though the spaces or occupied by pyrite are still recognizable. *B* shows that the oxidation banding is in a general way inde of the original rock texture. It will be noted, however, that very little iron oxide has developed phenocrysts.



A.



B.

LIESEGANG RINGS OF FERROUS AND FERRIC HYDROXIDES DEVELOPED IN AGAR AGAR BY DIFFUSION FROM OPPOSITE ENDS OF TUBES OF IRON SULPHATES AND SODIUM HYDROXIDE.

A. After 17 days. A is the first and B the second ring formed.
B. After one month. Most of the rings were ferrous hydroxide, but in the late stages, when the iron solution had oxidized, rings of ferric hydroxide were developed at A.

OXIDATION BANDING IN WALL ROCKS.

A feature of no economic importance but of some scientific interest is the regularly banded distribution of hydrous oxides of iron in certain of the wall rocks. This feature is especially well shown in material from the dump of the Valley View shaft, and most of the specimens studied were from that source. Similar banding was noted in place in the walls of the South vein, Desert Queen mine, at a depth of about 500 feet.

The agents producing this banding evidently gained access to the wall rock through fractures and from them permeated the rock. Polygonal blocks bounded by fractures show completely concentric structures such as are illustrated in Plate XIII, *B*.

The iron oxides appear to have been derived from the oxidation of pyrite, for in many specimens cores carrying abundant disseminated grains of pyrite remain. This is true of the specimen illustrated in Plate XIV, *A*, the light-colored, unbanded portion carrying abundant pyrite grains. Plate XV shows photomicrographs taken at the junction of the oxidized and unoxidized areas. Plate XV, *A*, taken in ordinary light, shows the scattered crystals of pyrite (black) in the unoxidized portion and irregular blotches of iron oxide, probably amorphous, in the oxidized portion. In the oxidized portion are visible several voids corresponding in size and shape to the pyrite crystals and evidently representing their former presence. Plate XV, *B*, gives the appearance of the same field in polarized light and shows that the oxidation banding is independent of the original texture of the rock.

Quartz veinlets that traverse the rock were at first believed to be later than the banding, but closer study leads to the conclusion that they were earlier. In places they have had surprisingly little influence on the course of the oxidation bands. Near some very late fractures the iron oxides have been leached.

A very interesting example of oxidation banding in fine-grained felsite from the vicinity of the North Star shaft is shown in Plate XIV, *B*. The senior writer was at first inclined to interpret this as a "development" by oxidation processes of a banded distribution of pyrite or ferruginous carbonates produced during hydrothermal metamorphism; microscopic study shows, however, that the position of the bands of iron oxide is wholly independent of the distribution of the pyrite from which it was plainly derived.

It has been suggested by A. C. Spencer that the banding is the result of alternate wetting and drying during many seasons. This explanation has much to recommend it in a region like Tonopah, where cyclonic storms are mainly confined to the winter months, the remainder of the year being rainless except for occasional showers. Furthermore, occasional drying permitting access of air would appear to be necessary for the oxidation of the pyrite.

The possibility of the development of such oxidation banding by diffusion processes analogous to the formation of the so-called Liesegang rings has been pointed out by Liesegang[1] and unquestionably merits serious consideration, although the progress of such processes must necessarily have been modified by alternations of wet and dry periods. In this connection two experiments carried out by the writers may be of interest.

In the first experiment the central portion of a straight glass tube about half an inch in internal diameter was filled with a solution of agar agar in water. This was retained in place by a wad of cotton until it hardened. After the agar agar had set to a firm jelly a solution of N/20 ferric sulphate was placed in one end of the tube and a solution of N/16 sodium hydroxide in the other end; the ends were then corked and sealed. After two days a faint brown band of ferric hydroxide had developed at the point marked *A* in Plate XVI, *A*. At the end of another two days the band *A* had not moved but was better defined and a new band of ferrous hydroxide (green) had developed at the point marked *B*. By the successive formation of new bands shown, from left to right in Plate XVI, *A* (from $Fe_2(SO_4)_3$ toward NaOH), the tube at the end of 17 days presented the appearance shown in the illustration. Bands once formed did not shift appreciably. The agar agar appears to have exerted a reducing influence on the ferric sulphate, so that most of the rings were of ferrous hydroxide instead of ferric hydroxide as was expected.

In a second experiment the agar agar was placed in the lower part of a U tube; sodium

[1] Liesegang, R. E., Geologische Diffusionen, pp. 106–116, 1913.

hydroxide was placed above it in one arm and ferrous hydroxide in the other. The appearance at the end of one month is shown in Plate XVI, *B*. Most of the rings were green, but those last formed, at the point marked *A*, were brown, evidently because of oxidation of the iron-bearing solution by the air.

Rings were also produced in compacted filter paper under conditions similar to those of the first experiment.

ANALYSES OF ORE, BULLION, ETC.

The following analyses, published by Mr. A. H. Jones[a] and inserted here with his permission, have significance in indicating the presence of certain elements, notably selenium, whose presence is not apparent from a mineralogic examination, and in showing that certain others, such as nickel and cobalt, which are characteristic of some silver deposits, are probably absent. For comparison the analysis by Hillebrand published in Spurr's report[b] is included.

Analyses of Tonopah ores, concentrates, bullion, etc.

	1	2	3	4	5
SiO_2	72.00	15.18	.....	5.50	.....
Al_2O_3	.42	.....	0.42	2.00	.....
CaO	3.10	3.70	.80	.10	.....
MgO	2.95	1.49	.....	Trace.	.....
$CaCO_3$	.....	.....	.....	3.60	.....
CO_2	.....	6.34	.....	.....	.....
NaCl and KCl	.....	.....	.....	1.00	.....
$FeSO_4$	.....	.....	.....	.26	.....
Fe	2.10	9.87	29.80	.....	.....
Mn	1.60	1.36	1.10	.....	.....
Cu	1.09	1.32	.60	2.10	1.02
Ni and Co	None.	.....	.....	.....	.....
Pb	1.50	6.21	1.30	2.36	2.41
Zn	3.00	5.84	.60	4.70	.06
Cd	None.	.....	.....	1.00	.....
As	Trace.	.19	.....	.....	.....
Sb	.10	.92	.....	.....	.....
Bi	None.	.....	.....	.....	.....
S	2.60	Not det	31.60	.....	.17
Se	.20	2.56	.....	1.40	1.80
Te	Trace.	None.	.....	.....	.....
Au	.06	.82	} 1.60	74.23	93.23
Ag	4.88	25.92			
Undetermined	[c]4.40	.....	1.58	[d]1.75	[b]1.31
Insoluble	.....	.....	30.60	.....	.....
	100.00	81.72	100.00	100.00	100.00

[a] By difference, mainly Na, K, and combined H_2O.

[b] By difference.

[c] Jones, A. H. (superintendent of mills, Tonopah Belmont Development Co.), The Tonopah plant of the Belmont Milling Co.: Am. Inst. Min. Eng. Trans., vol. 52, pp. 1731–1738, 1916.

[d] Spurr, J. E., Geology of the Tonopah mining district, Nev.: U. S. Geol. Survey Prof. Paper 42, p. 89, 1905.

1. Analysis by A. H. Jones of piece of rich silver ore from Belmont mine; exact location in mine unknown.

2. Analysis by W. F. Hillebrand, in the laboratory of the United States Geological Survey, of sulphides separated by crushing and panning from sample of rich sulphide ore from Montana vein at depths of 460 to 512 feet in Montana Tonopah mine.

3. Partial analysis by A. H. Jones of concentrates from Belmont mill.

4. Analysis by A. H. Jones of zinc box precipitate, Belmont mill.

5. Analysis by A. H. Jones of bullion, Belmont mill.

The cadmium shown in analysis 4 very possibly represents a concentration of cadmium occurring as an impurity in the zinc used for precipitation. It is noteworthy that the ratio of gold to selenium is very nearly the same in both analyses 1 and 2.

IDENTIFICATION OF METALLIC MINERALS IN POLISHED SECTIONS.

Some of the methods of identification of minerals in polished section that were used in these studies may include a few new points of possible service to other students of ore deposits.

Whenever possible small fragments of the mineral to be identified were chipped from the edges of the polished specimen with a stout needle or very sharp steel prod and tested before the blowpipe or in a wet way.

Needles of several sizes mounted in the ends of wooden penholders were found very useful as prods for testing the hardness, streak, sectility, etc., of minerals.

Most reagents for tarnishing the minerals can be conveniently applied on a strip of blotting paper about half an inch wide and 3 inches long. One end of this strip is moistened with the reagent and is rubbed lightly back and forth over the polished surface of the mineral, the progress of the tarnishing being watched under the low or moderate powers of the microscope and checked at the desired stage by simply rubbing with the dry end of the blotting paper.

Reactions aiding in the identification of certain minerals are the following:

The bright silvery luster of galena in polished sections, its lead-gray streak, and the development of triangular pits due to the tearing out of inverted pyramids of galena between the three sets of cleavage planes during polishing (see, for example, Pl. VII, *B*) have usually been considered sufficient to identify it. The writers discovered, however, that another min-

eral, probably a lead-silver sulphide, also possesses these characteristics. It was found that the two could be differentiated by treatment with ordinary commercial hydrogen peroxide (H_2O_2). This reagent tarnishes galena brown but does not affect the supposed lead-silver sulphide or any of the other silver minerals with which galena is commonly associated. It is therefore a reagent of great utility in studying the relations between galena and associated silver minerals. The tarnish it produces on galena appears slowly, can be quickly checked, and can be easily removed by a little polishing with rouge on a bit of cotton.

The polished surfaces of argentite usually appear slightly "rougher" under the microscope than most of the other sulphides with which it is associated except pyrite; this feature is well shown in Plate III, *B*. Pricking with a fine needle reveals its soft sectile character. It is unaffected by hydrogen peroxide and silver nitrate but is rapidly tarnished brown by saturated mercuric chloride solution.

Polybasite is brittle and gives a black streak. Its polished surfaces are unaffected by hydrogen peroxide but are tarnished reddish brown by silver nitrate solution and rapidly tarnished brown by saturated mercuric chloride solution.

Pyrargyrite is brittle and gives a red streak. It is unaffected by hydrogen peroxide but is tarnished brown by silver nitrate solution, though much more slowly than polybasite. Short treatment with saturated mercuric chloride solution tarnishes it pale brownish yellow; polybasite by the same treatment is tarnished a pronounced brown. The polybasite shown in Plate IV, *B*, has been differentiated from the pyrargyrite which incloses it by such treatment. Before treatment the two minerals were hardly distinguishable from each other.

Silver nitrate is a useful reagent for tarnishing chalcopyrite, which becomes reddish yellow, then deep amber, and finally madder-red; argentite, galena, and sphalerite are unaffected by the same treatment.

SUMMARY OF MORE IMPORTANT CONCLUSIONS.

1. The hypogene or primary ores have been modified in places by oxidation and enrichment through the agency of the air and oxygenated solutions originating at or near the surface. The high silver content of much of the ore obtained in the past and of son ore now remaining is unquestionably due part to these processes.

2. There is evidence not only of rece oxidation of the ores but also of at least o period of ancient oxidation, and superge sulphide enrichment was probably an acco paniment of each of these periods.

3. The rich silver ores now being mined Tonopah are probably in the main of hypoge or primary origin.

4. Mining has shown that in certain vei the primary sulphides become less abunda with increasing depth, though the same speci are present; mere increase in depth may accou for this change in some veins, for every ve must finally end in depth as well as laterally; many veins change in wall rock has been least a contributing factor. The veins deve oped by other deep workings are heavily mine alized and of high grade, and the geologic ev dence is favorable to the persistence of ri primary silver ores to depths considerab greater than those yet attained in the mini operations.

Although hot ascending waters are encou tered in a number of the deeper working there is little evidence that these waters a now depositing ores.

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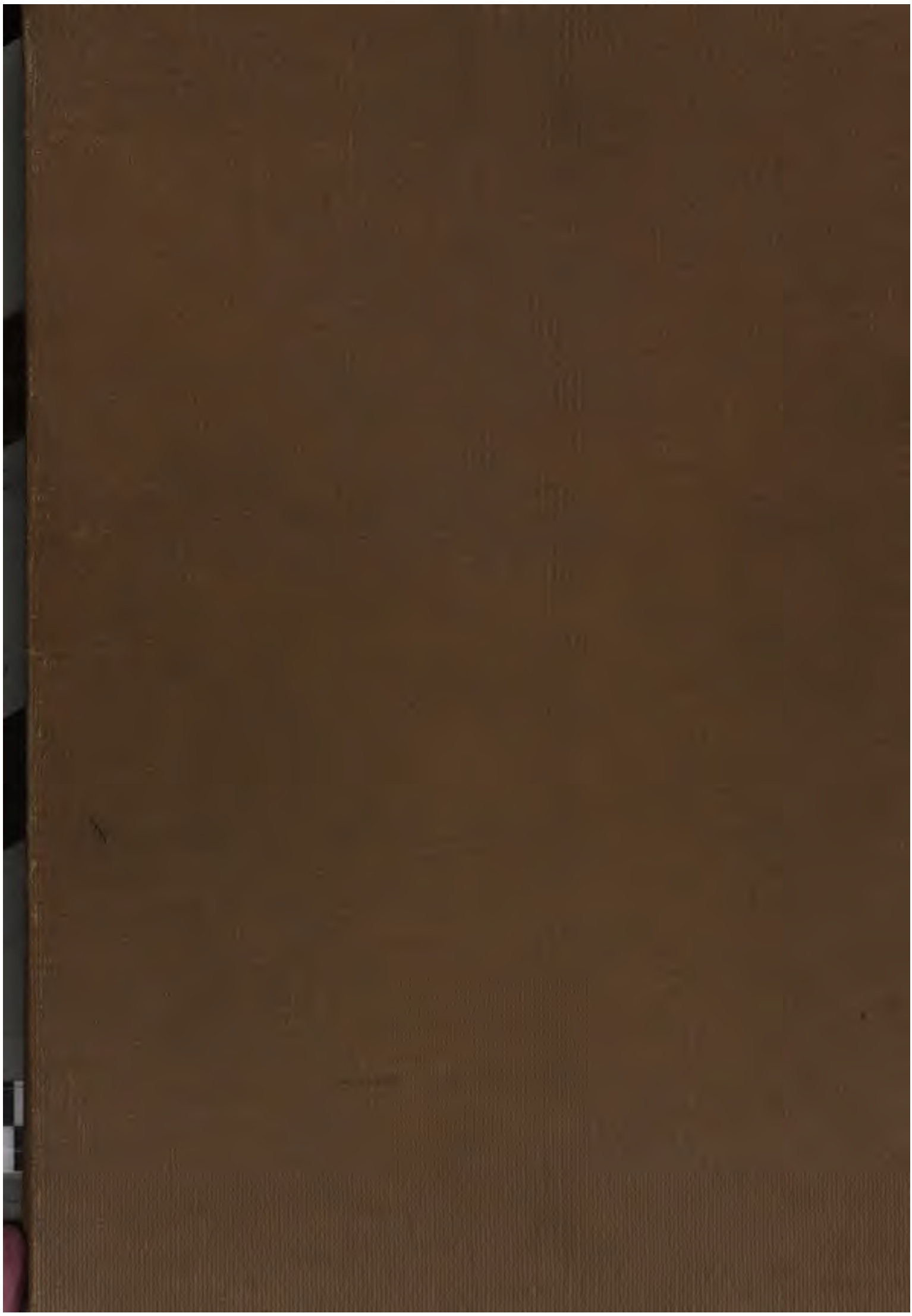
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